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INNOVATIVE TECHNOLOGY EVALUATION REPORT

Radio Frequency Heating, KAI Technologies, Inc.

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OFFICE OF RESEARCH AND DEVELOPMENT
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NOTICE

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FOREWORD

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments. The SITE Program is a joint effort between the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD) and Office of Solid Waste and Emergency Response. The purpose of the program is to enhance the development of hazardous waste treatment technologies necessary for implementing new cleanup standards that require greater reliance on permanent remedies. This is accomplished by performing technology demonstrations designed to provide engineering and economic data on selected technologies.

This project consisted of an evaluation of an in situ radio frequency heating (RFH) technology developed by KAI Technologies, Inc. (KAI). As a part of this evaluation, a Demonstration Test was conducted by the 'SITE Program in coordination with research efforts sponsored by the U.S. Air Force (USAF). During the demonstration, the KAI in situ RFH system was used to heat soil containing organic contaminants. The goals of the SITE Program study, summarized in this Innovative Technology Evaluation Report were: 1) to assess the ability of in situ RFH to remove organic contaminants from a contaminated site at Kelly Air Force Base and 2) to develop capital and operating costs for the technology.

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E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

The KAI Technologies radiofrequency heating system was demonstrated at Site S-1 at Kelly Air Force Base in San Antonio, Texas. Site S-1 was formerly used for intermediate storage of wastes destined for reclamation and was contaminated with mixed solvents, carbon cleaning compounds, petroleum oils and lubricants at depths up to 30 feet. The radiofrequency heating system was to be used to heat the soil to facilitate the removal of these contaminants via soil vapor extraction. A separate soil vapor extraction system was used for this demonstration, but was not evaluated as part of this demonstration.

Results of this demonstration indicate that contaminant removal (measured as TRPH) varied between 29 % and 42 % . Reasons behind the results observed are discussed in this report. A cost analysis of the use of the technology is also presented.

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ABBREVIATIONS

AC	Alternating Current	OSC	on-scene coordinator
ACGIH	American Conference of Governmental Industrial Hygienists	OSHA	Occupational Safety and Health Administration
AFB	Air Force Base	OSWER	Office of Solid Waste and Emergency Response
ANGB	Air National Guard Base	PCB	polychlorinated biphenyl
ARAR	Applicable or Relevant and Appropriate Requirement	PPE	personal protective equipment
ASTM	American Society for Testing and Materials	ppm	parts per million
ATTIC	Alternative Treatment Technology Information Center	PQL	Practical quantitation limit
bgs	below ground surface	QA/QC	quality assurance/quality control
B&RE	Brown & Root Environmental	RCRA	Resource Conservation and Recovery Act
CAA	Clean Air Act	RF	radio frequency
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act	RFH	radio frequency heating
CERI	Center for Environmental Research Information	RI/FS	remedial investigation/feasibility study
CFR	Code of Federal Regulations	RPM	remedial project manager
CPR	cardiopulmonary resuscitation	RREL	Risk Reduction Engineering Laboratory
CWA	Clean Water Act	SAIC	Science Applications International Corporation
DOT	Department of Transportation	SARA	Superfund Amendments and Reauthorization Act
EPA	Environmental Protection Agency	SDWA	Safe Drinking Water Act
FCC	Federal Communication Commission	SITE	Superfund Innovative Technology Evaluation
FID	flame ionization detector	SVE	Soil vapor extraction
ITER	Innovative Technology Evaluation Report	S V O C	Semivolatile organic compound
KAI	KAI Technologies, Inc.	TLV	Threshold Limit Value
LDR	Land Disposal Restrictions	TRPH	Total recoverable petroleum hydrocarbons
MCL	Maximum Contaminant Level	TSD	Treatment, Storage, and Disposal
MDL	Method Detection Limit	TSCA	Toxic Substances Control Act
MS/MSD	Matrix spike/Matrix spike duplicate	USAF	U.S. Air Force
NAAQS	National Ambient Air Quality Standards	VISITT	Vendor Information System for Innovative Treatment Technologies
NPDES	National Pollutant Discharge Elimination System	v o c	Volatile organic compound
ORD	Office of Research and Development		

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EXECUTIVE SUMMARY

This document is an evaluation of the performance of an in situ radio frequency heating (RFH) system developed by KAI Technologies, Inc. (KAI). This report examines data from the demonstration concerning the technical and economic aspects of KAI's RFH technology, particularly its ability to remediate soil contaminated with organics.

A demonstration of KAI's in situ RFH system was conducted from January 1994 to July 1994 at Kelly Air Force Base in San Antonio, Texas. This demonstration was conducted as a joint effort of the U. S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program and the U.S. Air Force (USAF).

EPA conducted pre- and post-treatment soil sampling and analysis. USAF provided the site for the test; necessary logistical and administrative support; and made arrangements with the technology developer, KAI, to operate its RFH process during the test.

Both EPA and USAF intend to prepare separate reports on this project. Each report will examine the data and results of the test in light of its own perspective. This report, prepared by EPA, discusses the results of the KAI demonstration with respect to the technology's potential Superfund applications.

The technology was never intended to remediate the site during the demonstration. Nevertheless, within certain limitations, changes in contamination levels within the area treated during the demonstration can be used to provide a very preliminary indication of how the technology in its present state of development might perform if used to remediate a site. These limitations include the fact that the technology is still being developed and may perform differently when used at a future date and at a different site. In addition, during the demonstration, implementation of the soil vapor extraction (SVE) system and other factors may have affected the data obtained from the demonstration, making it difficult to isolate the effect of the RFH on contaminant removal from the soil. These limitations are discussed in more detail in the report.

KAI Technologies disagrees with the use of data from the demonstration to predict performance in an actual remediation. For a more detailed discussion of KAI's perspective on the results of the demonstration, please see Vendor's Claims in Appendix C

The RFH technology uses electromagnetic energy in the radio frequency (RF) band to heat contaminated soil in situ, thereby potentially enhancing the performance of standard SVE technologies. The RF energy volatilizes contaminants and moisture in the soil, and the resulting steam and contaminant vapors are collected by a standard SVE system.

The demonstration began with initial sampling conducted from January 11, 1994 through January 19, 1994, during the installation of the subsurface system components. RF energy was applied to the soil from April 24, 1994 through June 7, 1994. The soil was allowed to cool for 1 month, and final sampling was conducted from July 7, 1994 to July 13, 1994. Based on the sampling data collected before and after treatment, an evaluation was made concerning the technology's ability to remove total recoverable petroleum hydrocarbons (TRPH) contamination from soil. This was considered the primary objective of the demonstration. Because RFH was actually applied only to the upper half of the original treatment zone, this upper region is designated the "revised treatment zone." A comparison of TRPH concentrations in the pre- and post-treatment soil samples within these two zones yielded the following results:

Within the original treatment zone there was a statistically significant change in TRPH concentrations at the 90 percent confidence level. The estimated geometric mean decrease was 29 percent. Concentrations in the pretreatment samples varied from less than 169 to 105,000 parts per million (ppm); post-treatment samples varied from less than 33 to 53,200 ppm.

Within the revised treatment zone there was a statistically significant change in TRPH concentrations at the 95 percent confidence level. The estimated geometric mean decrease was 49 percent. Concentrations in the pretreatment samples varied from less than 169 to 6,910 ppm; post-treatment samples varied from less than 33 to 4,510 ppm.

Outside the original treatment zone there was a statistically significant change in TRPH concentrations at the 97.5 percent confidence level. The estimated geometric mean increase was 90 percent. Concentrations in the pretreatment samples varied from less than 171.5 to 43,500 ppm; post-treatment samples varied from 762 to 92,600 ppm.

concentrations at the 80 percent confidence level. The estimated geometric mean increase was 39 percent. Concentrations in the pretreatment samples varied from less than 171.5 to 105,000 ppm; post-treatment samples varied from 184 to 92,600 ppm.

Contaminant removals did not meet projections. Before the RFH system was turned on, USAF and KAI made the decision to apply heat to the revised treatment zone. They targeted only volatile organics, specifically gasoline-range hydrocarbons, as the contaminants of concern, which allowed KAI to lower the treatment temperature from 150°C to a range of 100 to 130°C. These changes were based on timing and funding limitations placed on the project by USAF just prior to startup. (No changes in the Demonstration Plan were made because the SITE Program was not informed about this decision until after post-treatment sampling was completed.)

A number of problems with the design and operation of the SVE system were identified after the demonstration was complete. These problems included vapor extraction wells screened below the revised treatment zone, which may have drawn contaminants into the cooler soil, and SVE system configurations which may have resulted in slow vapor flows within the revised treatment zone and in high vapor flows from areas outside the revised treatment zone. These problems may have resulted in contaminant migration into the original treatment zone from the revised treatment zone and from surrounding soils. In addition, only a portion of the revised treatment zone appears to have reached the revised target temperature range of 100 to 130°C, which was at least partly due to a power supply problem unrelated to the operation of the KAI RFH system.

Because of changes in the RFH system prior to startup and the design of the SVE system, it cannot be concluded that the changes in TRPH concentration inside and outside the treatment zones were a result of RFH treatment. The soil data indicate changes in TRPH concentration, but it is not possible to determine what impact RFH had on contaminant removal rates, with the alternative being using the SVE system alone.

An economic evaluation was performed based on the original design of the RFH system for the demonstration. Because of the problems encountered during the demonstration, several assumptions had to be made about the technology. Even though no conclusions about the success of RFH at this site can be made, the economic evaluation assumes the technology will meet target cleanup levels within a given time frame. The results of this evaluation are as follows:

The cost to treat approximately 10,000 tons of contaminated soil using a proposed full-scale in situ RFH system (including costs associated with SVE) was estimated by scaling up costs for the original treatment zone. Cleanup costs are estimated to be \$336 per ton if the system is utilized 95 percent of the time. This estimate does not include costs for several site- and project-specific factors.

In addition to evaluating changes in TRPH concentrations, evaluations were made concerning the technology's ability to remove semivolatile organic compounds (SVOCs) and volatile organic compounds (VOCs) from soil. These were considered secondary objectives of the demonstration.

A comparison of SVOC concentrations in the pre- and post-treatment soil samples within the original treatment zone indicated that only benzo(b)fluoranthene, benzo(a)pyrene, and bis(2-ethylhexyl)phthalate exhibited statistically significant decreases at a confidence level of 80 percent or greater. In the revised treatment zone, benzo(b)fluoranthene, benzo(a)pyrene, chrysene, pyrene, and fluoranthene only exhibited statistically significant decreases at a confidence level of 80 percent or greater. Estimated mean decreases for SVOCs in the original and revised treatment zones are presented in Table 1.

Table 1. Summary of SVOC Decreases Inside Treatment Zones

contaminant	Geometric Mean Percent Decrease in Original Treatment Zone	Geometric Mean Percent Decrease in Revised Treatment Zone
Benzo(b)fluoranthene	44	40
Benzo(a)pyrene	44	43
Bis(2-ethylhexyl)phthalate	55	**
Chrysene	**	40
Pyrene	**	60
Fluoranthene	**	53

** No statistically significant change at the 80 percent confidence level.

As with the TRPH data, it cannot be concluded that the changes in SVOC concentrations inside and outside the treatment zones were a result of RFH treatment or were due solely to the application of SVE. Pre- and post-treatment concentrations of individual VOCs were also measured, but an evaluation of these data did not indicate any statistically significant decreases. No conclusions about changes in VOC concentrations can be made.

The KAI RFH technology was evaluated based on the nine criteria used for decision-making in the Superfund feasibility study process. Table 2 presents the evaluation.

Table 2. Evaluation Criteria for the KAI RFH Technology

Evaluation Criteria	Performance
Overall Protection of Human Health and the Environment	<p>The contaminant removals achieved may not provide adequate protection.</p> <p>Requires measures to protect workers during installation and treatment.</p> <p>During the limited time period of the SITE demonstration, soil samples exhibited estimated average TRPH decreases of 29% in the original treatment zone and 49% in the revised treatment zone.</p>
Compliance with Federal ARARs ¹	<p>Vapor collection and treatment are needed to ensure compliance with air quality standards.</p> <p>Construction and operation of onsite vapor treatment unit may require compliance with location-specific ARARs.</p> <p>RF generator must be operated in accordance with Occupational Safety and Health Administration (OSHA) and Federal Communication Commission (FCC) requirements.</p>
Long-term Effectiveness and Performance	<p>The contaminant reductions observed during the demonstration period show that the RFH technology may not adequately remove the contamination source.</p> <p>Involves some residuals treatment (vapor stream).</p>
Reduction of Toxicity, Mobility, or Volume through Treatment	<p>Potentially reduces waste volume by volatilizing contaminants, which are then collected (in a more concentrated form) by an SVE system.</p> <p>Potentially reduces long-term contaminant mobility by volatilizing contaminants, which are then removed from the soil and collected by an SVE system.</p>
Short-term Effectiveness	<p>Presents minimal short-term risks to workers and community from air release during treatment.</p> <p>No excavation is required, although drilling will disturb the soil to some extent.</p>
Implementability	<p>RF generator must be operated in accordance with OSHA and FCC requirements.</p> <p>Other pilot-scale tests have been completed; no full-scale applications to date.</p>
Cost ²	<p>\$336 per ton based upon scaling up the pilot-scale, manually- operated system to full-scale, with 95% on-line efficiency.</p>
State Acceptance	<p>No excavation is required, which should improve State acceptance.</p>
Community Acceptance	<p>No excavation is required, which should improve community acceptance.</p> <p>May require some community education to assure residents that the operation of the RFH system is compliant with OSHA safety requirements.</p>

¹ = Applicable or Relevant and Appropriate Requirements

² Actual cost of a remediation technology is highly site-specific and dependent on the original target cleanup level, contaminant concentrations, soil characteristics, and volume of soil. Costs associated with permitting, site preparation, analytical programs, and residuals management were not included. Cost data presented in this table are based on the treatment of approximately 10,000 tons of soil (95% on-line efficiency), and include costs associated with SVE. It assumes target cleanup levels will be met within a given time frame, even though this was not observed during the demonstration.

SECTION 1

INTRODUCTION

This section provides background information regarding the Superfund Innovative Technology Evaluation (SITE) Program, discusses the purpose of this Innovative Technology Evaluation Report (ITER), and describes the in situ radio frequency heating (RFH) technology developed by KAI Technologies, Inc. (KAI). For additional information about the SITE Program, this technology, and the demonstration site, contact the individuals listed at the end of this section.

1.1 BACKGROUND

A Demonstration Test of KAI's RFH technology was conducted by the SITE Program in coordination with research efforts sponsored by the U.S. Air Force (USAF). Although the technology was developed by KAI, Brown & Root Environmental (B&RE) was EPA's primary contact during the demonstration. B&RE was hired by USAF to provide an evaluation of KAI's RFH technology. (The USAF contract was awarded to Halliburton NUS, which has since reorganized. The work was performed by B&RE which is owned by Halliburton NUS.) B&RE provided project and site management, designed and operated the vapor collection and treatment systems, provided logistical support, and assisted KAI in the onsite assembly and operation of the RFH system. KAI was subcontracted by B&RE to operate its Mobile RFH system with an applicator design adapted for the Kelly Air Force Base (AFB) test environment.

The KAI RFH process was demonstrated under the SITE Program from January 1994 through July 1994 at Kelly AFB near San Antonio, Texas. The SITE demonstration was conducted at Site S-1, located near the northern boundary of Kelly AFB. This site was historically used as an intermediate storage area for wastes destined for offsite reclamation. The soil is contaminated with mixed solvents, carbon cleaning compounds, and petroleum oils and lubricants. The results of the Demonstration Test constitute the basis for this report.

The RFH technology uses electromagnetic energy in the radio frequency (RF) band to heat contaminated soil in situ. Standard alternating current (AC) electricity is converted to RF energy by an

RF generator. The RF energy is conveyed into the soil by one or several antennae. The design temperature will vary from site to site, depending on the contaminants of concern. KA1 claims that the RFH technology can be applied to soil contaminated with volatile and semivolatile organic compounds (VOCs and SVOCs), which are volatilized when the soil is heated. Soil moisture is also volatilized during treatment and may provide a steam sweep within the treatment zone. A vacuum is applied to the treatment zone, and the steam and organic vapors are collected and channeled to an above-ground vapor treatment system. A vapor barrier assists in the collection of the hot gases and prevents fugitive emissions.

1.2 BRIEF DESCRIPTIONS OF THE SITE PROGRAM AND REPORTS

In 1986, the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) established the SITE Program to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its ninth year, the SITE Program is helping to provide the treatment technologies necessary to implement new Federal and State cleanup standards aimed at permanent remedies rather than quick fixes. The SITE Program is composed of four major elements: the Demonstration Program, the Emerging Technologies Program, the Measurement and Monitoring Technologies Program, and the Technology Transfer Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data for selected technologies. To date, the Demonstration Program projects have not involved funding for technology developers. EPA and developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems at chosen sites, usually Superfund sites. EPA is responsible for sampling, analyzing, and evaluating all test results. The final product of each demonstration is an assessment of the technology's performance, reliability, and costs. This information is used in conjunction with other data to select the most appropriate technologies for the cleanup of Superfund sites.

Developers of innovative technologies typically apply to the Demonstration Program by responding to EPA's annual solicitation. EPA also accepts proposals any time a developer has a Superfund waste treatment project scheduled. To qualify for the program, a new technology must be available as a pilot- or full-scale system and offer some advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA has accepted a proposal, EPA and the developer work with the EPA Regional Offices and State agencies to identify a site containing waste suitable for testing the capabilities of the technology. EPA prepares a detailed sampling and analysis plan designed to evaluate the technology thoroughly and to ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several years, depending on the length of time and quantity of waste needed to assess the technology.

KAI entered the SITE Program through a cooperative agreement between USAF and EPA. USAF invited EPA to participate in the demonstration to provide sampling and analytical services. EPA would then publish reports based upon the outcome of the demonstration.

The results of the KAI RFH Technology Demonstration are published in two documents: the ITER and the SITE Technology Capsule. The ITER includes information on demonstration costs and performance, implementation problems/limitations, site conditions for which the technology is applicable, waste handling requirements, and an evaluation of the technology with consideration of the nine criteria used by remedial project managers (RPMs) during the remedial investigation/feasibility study (RI/FS) process. The ITER also describes the demonstration, the developer's experience prior to the demonstration, and the adaptability of the technology. The SITE Technology Capsule is a concise summary of the ITER. Both the SITE Technology Capsule and the ITER are intended for use by RPMs making a detailed evaluation of the technology for a specific site and waste.

The second element of the SITE Program is the Emerging Technologies Program, which fosters the further investigation and development of treatment technologies that are still at the laboratory scale. Successful validation of these technologies can lead to the development of a system ready for field demonstration and participation in the Demonstration Program.

The third component of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies to characterize Superfund sites.

The fourth component of the SITE Program is the Technology Transfer Program, which reports and distributes the results of both Demonstration and Emerging Technologies Program studies through ITERs and abbreviated bulletins.

1.3 PURPOSE OF THE ITER

This ITER provides information on the KAI RFH technology and includes a comprehensive description of the demonstration and its results. The ITER is intended for use by EPA RPMs, on-scene coordinators (OSCs), contractors, and others involved in the remediation decision-making process and in the implementation of specific remedial actions. The ITER is designed to aid decision makers in determining whether specific technologies warrant further consideration as applicable options in particular cleanup operations. To encourage the general use of demonstrated technologies, EPA provides information regarding the applicability of each technology to specific sites and wastes. The ITER includes information on cost- and site-specific characteristics. It also discusses advantages, disadvantages, and limitations of the technology.

This report presents information useful in determining the applicability and estimated cost of using a full-scale RPH system at a Superfund site. The proposed commercial-scale system, which utilizes a 200-kilowatt (kW) RF generator, is described in this document. The applicability of the proposed system and treatment costs for a full-scale remediation using the 200-kW system are presented. Costs are presented on a per ton basis to facilitate comparison to other available technologies.

Each SITE demonstration evaluates the performance of a technology in treating a specific waste. The waste characteristics of other sites may differ from the characteristics of the waste treated at the demonstration site. Therefore, successful field demonstration of a technology at one site does not necessarily ensure that it will be applicable to other sites. Data from the field demonstration may require extrapolation for estimating the operating ranges in which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field demonstration.

1.4 TECHNOLOGY DESCRIPTION

RPH technologies use RF energy to heat soil in situ, thereby potentially enhancing the performance of standard SVE technologies. The RF energy heats the soil by a dielectric heating process that does not rely on soil permeability or conductive heat transfer mechanisms. The developer claims that, for low thermal conductivity solids, RFH is a faster and more efficient heating mechanism than convective or radiative heating processes. Some conductive heating also occurs in the soil. It is potentially applicable to unsaturated (vadose zone) soils contaminated with VOCs and SVOCs. Moisture present in the soil is also volatilized and may provide a steam sweep within the treatment zone. Steam

and contaminant vapors are collected by a standard soil vapor extraction (SVE) system and channeled to a vapor treatment system. The vapor treatment system is site- and contaminant-specific, and therefore was not included in this evaluation. A basic schematic of the RFH system used during the SITE demonstration is shown in Figure 1.

The components of the KAI RFH system have three major purposes: transmission, monitoring, and control of RF energy; collection of vapors; and treatment of vapors. The primary components of the system include the following:

- **RF Generator** – The RF generator is designed to convert 3-phase AC power to RF energy. A typical system is designed to operate on one or more Industrial, Scientific, and Medical (ISM) bands designated by the Federal Communications Commission (FCC). The RF generator used during the SITE demonstration was operated at 27.12 megahertz (MHz) with a maximum power level of 25 kW.
- **Matching Network** – The RFH system also includes a matching network, which allows the RFH system to maximize the fraction of the power from the RF generator that is absorbed by the soil. This is important for two reasons. First, the higher the fraction of power absorbed by the soil, the more energy-efficient the system. Second, power that is not absorbed by the soil is reflected back to the RF generator and other electrical components. Excessive reflected power will cause the electrical components to overheat. The developer claims that full automation of the matching network is possible. During the demonstration, however, there was always at least one person onsite when the RF power was on.
- **Diagnostic and Control System** – The diagnostic and control system is used to monitor the operation of the complete RFH system. The developer claims that the control computer allows for complete, unattended operation with remote control and alarm functions. During the demonstration, however, there was always at least one person onsite when the RF power was on.
- **Applicators** – Energy from the RF generator flows through the matching network to the applicators, which convey the energy into the soil. The two applicators used during the demonstration were connected with rigid copper transmission lines that were pressurized with nitrogen to increase their high voltage handling capability. The applicators were alternately selected with a remote-controlled coaxial switch. Each applicator was 3.5 inches in diameter and was constructed with aluminum, stainless steel, Teflon[®], ceramic, brass, and copper components.
- **Temperature Measuring Devices** – Soil temperature in and around the treatment zone is monitored during treatment. During the SITE demonstration, soil temperatures were measured using thermocouples, fiberoptic sensors, and infrared sensors. Temperature measurement locations are shown in Figure 1. All sensors within the revised treatment zone measured temperature indirectly through fiberglass walls or sand barriers. Temperature measurements obtained from active extraction wells may have been reduced by air flowing through the SVE system. The developer claims that there were no sensors within the revised treatment zone that measured the instantaneous, microscopic heating of the contaminants, and

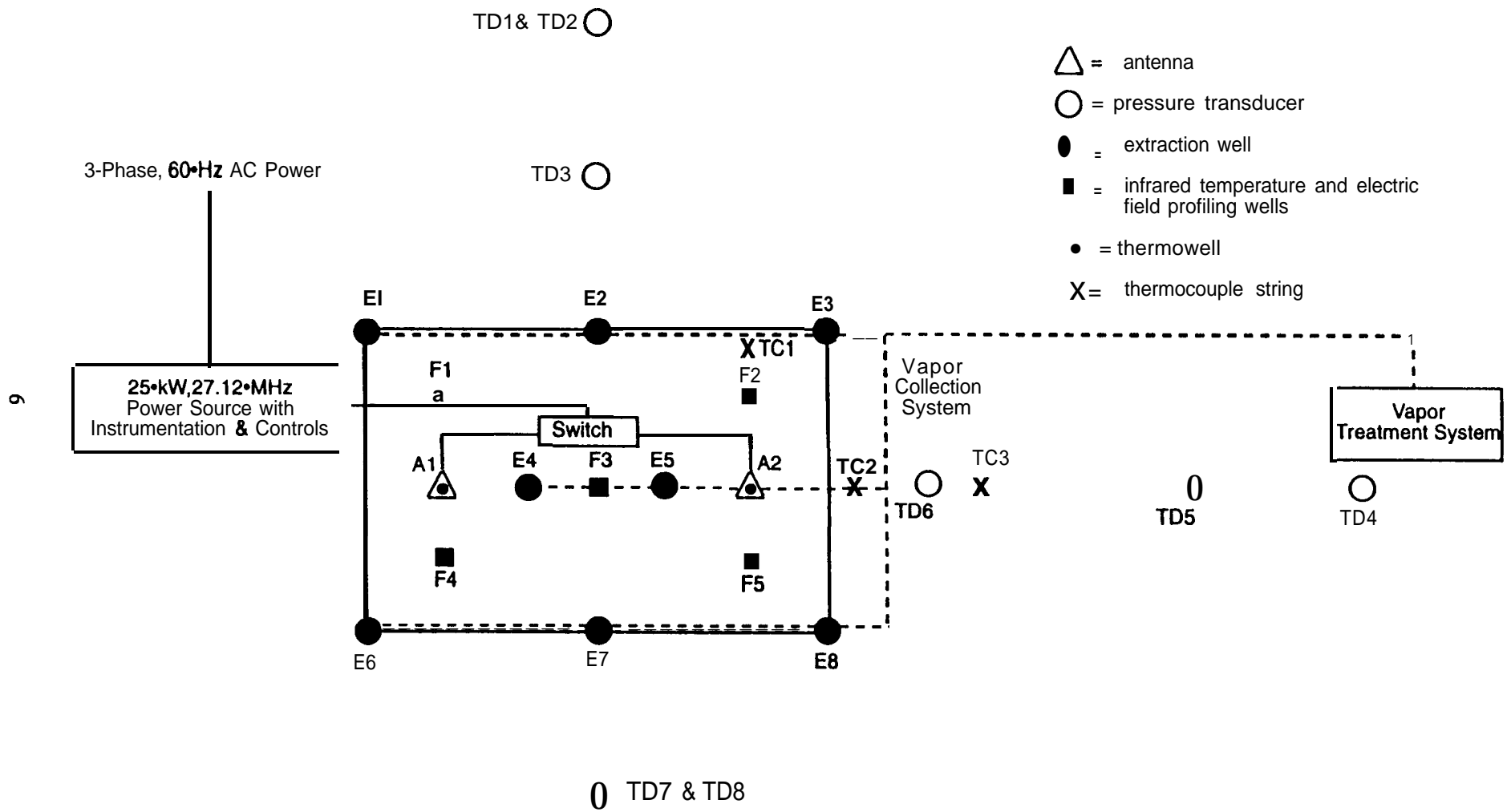


Figure 1. Diagram of KAI RFH system.

that all sensors were likely to provide readings lower than the actual temperatures of the materials in the heated zone. No data were provided to support these claims.

- **Electromagnetic Field Measuring Devices**— The electromagnetic field generated by the RF energy is measured in and around the treatment zone to determine whether the system is complying with all regulations concerning electromagnetic fields. During the SITE demonstration, a magnetic field sensor was inserted into five wells to monitor the electromagnetic field within the treatment zone. Two antenna-based devices were used to measure the electromagnetic fields above the surface: an electric field radiation hazard sensor was used near the system, and a biconical dipole antenna was used at distances of 1 meter, 10 meters, 30 meters, and 300 meters.
- **Pressure Transducer Wells** — Pressure transducer wells can be installed to determine the effects of the SVE system. Prior to and during the SITE demonstration, the vacuum caused by the SVE system was measured at the pressure transducer wells. Vacuum measurements were also taken at the extraction wells.
- **Vacuum Manifold** — The extraction wells feed into a vacuum manifold, which gathers the vapors together and channels them into the vapor treatment system.
- **Vacuum Source** — A vacuum is induced throughout the treatment zone by pulling air through the vacuum manifold and extraction wells. During the SITE demonstration, an air compressor and a Venturi tube were used to induce a vacuum. In a full-scale system, a blower would typically be used.
- **Vapor Barrier** — The system includes a vapor barrier to prevent the release of volatilized contaminants and to help to maintain a vacuum in the treatment zone. During the SITE demonstration, a sheet of heavy plastic served as a vapor barrier.
- **Vapor Treatment System** — Contaminant vapors removed from the treatment zone must typically be collected or treated. During the SITE demonstration, vapors that condensed in the vapor collection system piping were collected as liquids. The uncondensed portion of the vapor stream was incinerated in a propane-fueled flare. Other sites may require more complex vapor treatment systems. Because the design of the vapor treatment system is site- and contaminant-specific, the vapor treatment system used during the SITE demonstration is not included in this evaluation.

The RFH system is transported to the site in a trailer with a removable steel shelter that houses the RF generator, matching network, and diagnostic and control equipment. The onsite assembly of the RFH system begins with the installation of the subsurface components. Extraction wells, temperature measurement wells, electromagnetic field measurement wells, and fiberglass borehole liners for the applicators are installed by drilling a hole to the required depth, inserting the appropriate component, and backfilling around the component. Support structures positioned above the applicator boreholes are used to insert the applicators into the fiberglass borehole liners. A portion of each subsurface component must extend above the surface to allow connection to the appropriate above-ground portion of the system.

After all subsurface components are installed, the vapor barrier is placed over the treatment zone. Holes are cut in the vapor barrier to allow connections between the subsurface components and the above-ground portions of the system. The vapor barrier is then sealed around each connection. Extraction wells are connected to the vapor treatment system through the vacuum manifold. Thermocouples are connected to monitoring instruments. The applicators are connected to the coaxial switch with RF transmission lines.

After all subsurface components are installed, the vapor barrier is placed over the treatment zone. Holes are cut in the vapor barrier to allow connections between the subsurface components and the above-ground portions of the system. The vapor barrier is then sealed around each connection. Extraction wells are connected to the vapor treatment system through the vacuum manifold. Thermocouples are connected to monitoring instruments. The antennae are connected to the RF generator and instrumentation by 1-5/8" rigid copper transmission lines.

After installation and assembly, the system is tested and any necessary adjustments are made. If desired, the SVE system may be operated before heat is applied to the soil. The SVE system continues to operate as the RF system is activated and heat is applied to the soil. The RF energy is applied to the soil until the termination criteria are met. Termination criteria should be established prior to the remediation effort based on treatability study results, site characterization data, and target cleanup levels. For application of RFH at Super-fund sites, factors such as average soil temperature in the treatment zone over a specified amount of time and contaminant concentrations in the vapor stream should be considered when determining termination criteria. The termination criteria may require adjustment based on information collected during treatment.

Because of time and funding constraints imposed on the developer by USAF, RFH was applied for a predetermined number of days before the RF power was turned off. These termination criteria may have limited the RFH system's ability to reach the target removal level.

After treatment is complete, the treatment zone must be allowed to cool. If the treatment zone did not encompass all of the contaminated soil at the site, the above-ground components of the RFH system can be disassembled, moved to another portion of the site, and reassembled while the soil in the treatment zone cools. If the commercial-scale system includes two sets of subsurface components, treatment of a second zone can begin while the first zone is cooling. During the SITE demonstration,

the soil was allowed to cool for 1 month prior to post-treatment sampling. The SVE system was operated for the first 14 days of the cool-down period.

After the treatment zone cools, post-treatment soil samples are collected to determine the extent of treatment. Depending upon local regulations, it may be necessary to remove all subsurface components, and then redrill and seal all boreholes. During the SITE demonstration, it was necessary to redrill all boreholes and seal them with bentonite at the end of the test.

1.5 KEY CONTACTS

For more information on the demonstration of the KAI in situ RFH technology, please contact:

- | | |
|---|---|
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Information on the SITE Program is also available through the following on-line information clearing houses:

- The Alternative Treatment Technology Information Center (ATTIC) is a comprehensive, automated information retrieval system that integrates data on hazardous waste treatment technologies into a centralized, searchable source. This data base provides summarized information on innovative treatment technologies. The system operator can be reached at (703) 908-2137, and system access is available at (703) 908-2138.
- The Vendor Information System for Innovative Treatment Technologies (VISITT) data base contains information on 154 technologies offered by 97 developers, (800) 245-4505.
- The OSWER CLU-IN electronic bulletin board contains information on the status of SITE technology demonstrations. The system operator can be reached at (301) 589-8268.

Technical reports can be obtained by contacting the EPA Center for Environmental Research Information (CERI), 26 West Martin Luther King Drive, Cincinnati, Ohio 45268 at (513) 569-7562.

SECTION 2

TECHNOLOGY APPLICATIONS ANALYSIS

This section addresses the applicability of the KAI in situ RFH technology to the remediation of soils contaminated with VOCs and SVOCs. Conclusions are based on results obtained from the SITE demonstration as well as additional data provided by KAI and B&RE. The results of the SITE demonstration are presented in Section 4 and supplementary data from the demonstration are presented in Appendix A. The results of previous RFH treatability studies are summarized in Appendix B.

2.1 OBJECTIVES: PERFORMANCE VERSUS ARARS

This subsection discusses specific environmental regulations pertinent to the operation of the KAI RFH system, including the transport, treatment, storage, and disposal of wastes and treatment residuals. The impact of these regulations will be evaluated in light of the demonstration results. State and local regulatory requirements, which may be more stringent, will also have to be addressed by RPMs. Applicable or relevant and appropriate requirements (ARARs) may include regulations associated with the following: the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); the Resource Conservation and Recovery Act (RCRA); the Clean Air Act (CAA); the Safe Drinking Water Act (SDWA); the Clean Water Act (CWA); the Toxic Substances Control Act (TSCA); and Occupational Safety and Health Administration (OSHA) regulations. These seven general ARARs are discussed in the following subsections; specific ARARs must be identified by RPMs for each site. Some specific Federal and State ARARs that may be applicable to the KAI RFH technology are identified and discussed in Table 3.

2.1.1 CERCLA

CERCLA of 1980, as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986, provides for Federal funding to respond to releases of hazardous substances to air, water, and land. Section 121 of SARA, Cleanup Standards, states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It strongly recommends that remedial actions use onsite treatment that ". . . . permanently and significantly reduces the volume, toxicity, or mobility of

Table 3. Potential Federal and State ARARs for the Treatment of Contaminated Soil by the KAI RFH System at a Superfund Site

Process Activity	ARAR	Description	Basis	Response
Waste characterization (untreated waste)	RCRA ¹ 40 CFR ² Part 261 or State equivalent	Identification and characterization of the soil to be treated.	A requirement of RCRA prior to managing the waste.	Chemical and physical analyses must be performed.
	TSCA ³ 40 CFR Part 761 or State equivalent	Standards that apply to the treatment and disposal of wastes containing polychlorinated biphenyls (PCBs).	During waste characterization, PCBs may be identified in the waste and, if present above regulatory thresholds (50 ppm for TSCA), the waste is subject to TSCA regulations.	Analysis for PCBs must be performed if potentially present.
Storage prior to processing	< 90 days: RCRA 40 CFR Part 262 or State equivalent	Standards applicable to the storage of hazardous waste in containers or tanks.	Contaminated groundwater extracted by dewatering wells and soil cuttings from boreholes meeting the definition of hazardous waste must meet substantive requirements of RCRA storage regulations.	Ensure storage containers and tanks are in good condition, provide secondary containment, when applicable, and conduct regular inspections.
	> 90 days: RCRA 40 CFR Part 264 or State equivalent			
Waste processing	RCRA 40 CFR Part 264 or State equivalent	Standards applicable to the treatment of hazardous waste at permitted facilities.	Treatment of hazardous waste must be conducted in a manner that meets the substantive requirements of a RCRA Part B permit.	Equipment must be operated, maintained, and monitored properly.
	CAA ⁴ 40 CFR or State equivalent	Standards applicable to emissions from treatment equipment.	Air emissions may have to be controlled to meet the substantive requirements of CAA permit.	Emission control devices may need to be installed to treat air emissions from the SVE unit.
Storage after processing	RCRA 40 CFR Part 264 or State equivalent	Standards that apply to the storage of hazardous waste in containers or tanks.	Contaminated groundwater extracted by dewatering wells, condensate, spent carbon (if used), and soil cuttings from boreholes meeting the definition of hazardous waste must meet substantive requirements of RCRA storage regulations.	The contaminated groundwater, condensate, and soil cuttings must be stored in containers or tanks that are well maintained.
	TSCA 40 CFR Part 761.65	Standards that apply to storage of wastes containing PCBs.	Groundwater, condensate, spent carbon (if used), and soil cuttings may contain PCBs above regulatory thresholds.	Ensure disposal of TSCA-regulated waste within 1 year of placement into storage.

1 RCRA is the Resource Conservation and Recovery Act.

2 CFR is the Code of Federal Regulations.

3 TSCA is the Toxic Substances Control Act.

4 CAA is the Clean Air Act.

5 CWA is the Clean Water Act.

6 SDWA is the Safe Drinking Water Act.

7 DOT is the Department of Transportation.

Table 3. (continued)

Process Activity	ARAR	Description	Basis	Response
Waste characterization (treated waste and residuals)	RCRA 40 CFR Part 261 or State equivalent	Identification and characterization of in situ soil, soil cuttings, spent carbon (if used), groundwater, and condensate.	A requirement of RCRA prior to managing the waste necessary to determine regulatory status of in situ soil.	Chemical and physical tests must be performed on the in situ soil, groundwater, soil cuttings, and condensate.
	TSCA 40 CFR Part 761 or State equivalent	Standards that apply to the treatment and disposal of wastes containing PCBs.	Soil cuttings, spent carbon (if used), and condensate may contain PCBs above regulatory thresholds.	Analysis for PCBs must be performed if PCBs were present in untreated soil.
Transportation for offsite disposal	RCRA 40 CFR Part 262 or State equivalent	Manifesting, packaging, and labeling requirements prior to transporting.	The contaminated groundwater, condensate, and soil cuttings may need to be manifested and managed as a hazardous waste.	An identification (ID) number must be obtained from EPA.
	RCRA 40 CFR Part 263 or State equivalent	Packaging, labeling, and transportation standards.	Transporters of hazardous waste must be licensed by EPA and meet specific requirements.	A licensed hazardous waste transporter must be used to transport the hazardous waste.
	DOT 49 CFR		Hazardous materials must meet specific packaging and labeling requirements.	Shipments of material must be properly containerized and labeled.
Groundwater and condensate discharge	CWA ⁵ 40 CFR Parts 301, 304.306, 307, 308, 402, and 403	Standards that apply to discharge of contaminated water into sewage treatment plants or surface water bodies.	The groundwater and condensate may not meet local pretreatment standards without further treatment or may require a NPDES permit for discharge to surface water bodies.	Determine if the groundwater and condensate could be discharged to a sewage treatment plant or surface water body without further treatment. If not, the water may need to be further treated to meet discharge requirements.
	SDWA ⁶ 40 CFR Parts 144 and 145	Standards that apply to the disposal of contaminated water in underground injection wells (including infiltration galleries).	Injection of the groundwater and condensate may be the preferred option for management of water from treatment at remote sites.	If underground injection is selected as a disposal means for treated water, testing must be performed and permission must be obtained from EPA to use existing permitted underground injection wells or to construct and operate new wells.

1 RCRA is the Resource Conservation and Recovery Act.

2 CFR is the Code of Federal Regulations.

3 TSCA is the Toxic Substances Control Act.

4 CAA is the Clean Air Act.

5 CWA is the Clean Water Act.

6 SDWA is the Safe Drinking Water Act.

7 DOT is the Department of Transportation.

hazardous substances. " In addition, the nine criteria used by RPMs during the RI/FS process must be addressed by CERCLA remedial actions. The criteria include:

- Overall protection of human health and the environment
- Compliance with ARARs
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, or volume
- Short-term effectiveness
- Implementability
- cost
- State acceptance
- Community acceptance

The performance of KAI's RFH technology in each of these nine categories was evaluated, and the results are presented in Table 1 in the Executive Summary.

2.1.2 RCRA

RCRA is the primary Federal legislation governing hazardous waste activities. Although a RCRA permit is not required for hazardous waste treatment for onsite remedial actions at Superfund sites, the KAI RFH system must meet all of its substantive requirements if treating a hazardous waste. RCRA administrative requirements such as reporting and recordkeeping, however, are not applicable for onsite actions. Subtitle C of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste. Compliance with these requirements is mandatory for CERCLA sites producing hazardous waste onsite.

The substantive requirements of a Part B Treatment, Storage, and Disposal (TSD) permit may be required when the soil undergoing treatment is considered to be hazardous. Invariably, a Uniform Hazardous Waste Manifest must accompany offsite shipment of RCRA hazardous wastes, and transport must comply with Federal DOT hazardous waste packaging, labeling, and transportation regulations. The receiving TSD facility must be permitted and in compliance with RCRA standards. The RCRA land disposal restrictions (LDR) in 40 CFR 268 preclude the land disposal of hazardous waste that fails to meet stipulated treatment standards. The technology or treatment standards applicable to the residuals produced by the KAI RFH system will be determined by the characteristics of the material treated and

the residuals generated. Wastes that do not meet these standards must receive additional treatment to bring the wastes into compliance with the standards prior to land disposal, unless a variance is granted.

2.1.3 CAA

The CAA establishes primary and secondary ambient air quality standards for the protection of public health and emissions limitations for certain hazardous air pollutants. Requirements under the CAA are administered by each state as part of the State Implementation Plans developed to bring each state into compliance with the National Ambient Air Quality Standards (NAAQS). The ambient air quality standards listed for specific pollutants will generally be applicable to the operation of the RFH system, since it volatilizes contaminants and removes them from the soil as vapors. A vapor barrier and vapor collection system (described in Subsection 1.4) prevent the release of these contaminants to the air. The system that will be used to treat the collected vapors varies depending on the location of the site and the contaminants present. The vapor treatment system must be designed in compliance with the CM. The operating permits required and allowable emission limits must be evaluated on a case-by-case basis.

The vapor treatment system employed during the SITE demonstration consisted of condensate collection and a propane-fueled flare. According to B&RE, the flare was operated under Standard Exemption Number 68 as defined in Section 382.057 of the Texas Clean Air Act. The vapor stream prior to the flare was periodically sampled prior to, during, and after RFH treatment. Vapor stream data are presented in Appendix A.

2.1.4 SDWA

SDWA establishes primary and secondary national drinking water standards. CERCLA refers to these standards and Section 121(d)(2) explicitly mentions two of these standards for surface water or groundwater: Maximum Contaminant Levels (MCLs) and Federal Water Quality Criteria. Alternate Concentration Limits (ACLs) may be used when conditions of Section 121 (d)(2)(B) are met and cleanup to MCLs or other protective levels is not practicable. Included in these sections is guidance on how these requirements may be applied to Superfund remedial actions. The guidance, which is based on Federal requirements and policies, may be superseded by more stringent promulgated State requirements, resulting in the application of even stricter standards than those specified in Federal regulations.

Approximately 2,000 gallons of condensate were collected from the vapor treatment system and transferred to the Kelly AFB industrial wastewater treatment facility for treatment. In other applications of the RFH technology, the amount of condensate generated and the contaminants present in the condensate will depend on the temperature to which the soil is heated, the moisture content of the soil, the contaminants present in the soil, and the design of the vapor treatment system. Aqueous residuals were also generated during equipment and personnel decontamination and treated as the condensate above. If commercial applications of the RFH technology require dewatering to lower the water table, groundwater residuals will also be generated.

2.1.5 CWA

CWA regulates direct discharges to surface water through the National Pollutant Discharge Elimination System (NPDES) regulations. These regulations require point-source discharges of wastewater to meet established water quality standards. The discharge of wastewater to a sanitary sewer requires a discharge permit or, at least, concurrence from State and local regulatory authorities that the wastewater is in compliance with regulatory limits. As discussed in Subsection 2.1.4, the aqueous residuals generated during the SITE demonstration were condensate from the vapor treatment system and washwater from equipment and personnel decontamination.

2.1.6 TSCA

The treatment and disposal of asbestos and materials containing PCBs at concentrations of 50 parts per million (ppm) or greater are regulated by TSCA. Asbestos is not generally present at the type of site that would be remediated using the RFH technology. It is possible that the RFH technology could be used to treat soil that contains PCBs. The regulation of treatment of PCB-contaminated materials is based on PCB concentration. Materials containing PCBs in concentrations between 50 and 500 ppm may be disposed of in TSCA-permitted landfills or incinerated in TSCA-approved incinerators; materials containing PCBs in concentrations greater than 500 ppm must be incinerated. It is permissible, however, to use other technologies to reduce the volume of material containing PCBs in concentrations less than 500 ppm. If RFH was used to treat material containing PCBs, the PCB vapors would require collection and condensation followed by disposal in accordance with TSCA.

Sites where PCB spills have occurred after May 4, 1987, must be addressed under the PCB Spill Cleanup Policy in 40 CFR Part 761, Subpart G. The policy applies to spills of materials containing PCBs

in concentrations of 50 ppm or greater and establishes cleanup protocols for addressing such releases based on the volume and concentration of the spilled material.

2.1.7 OSHA Requirements

CERCLA remedial actions and RCRA corrective actions must be performed in accordance with OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provides for the health and safety of workers at hazardous waste sites. Onsite construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part B of OSHA, which provides safety and health regulations for construction sites. State OSHA requirements, which may be more stringent than Federal standards, must also be met.

All personnel involved in the operation of the KAI RFH system must have completed a 40-hour OSHA training course covering personal protective equipment (PPE), safety and health, emergency response procedures, and quality assurance/quality control (QA/QC). Additional training addressing the site activities, procedures, monitoring, and equipment associated with the technology is also necessary. Training provided prior to the operation of the system should include information regarding emergency evacuation procedures; safety equipment locations; the boundaries of the exclusion zone, contaminant reduction zone, and support zone; and PPE requirements. Onsite personnel must also participate in a medical monitoring program. Health and safety monitoring and incident reports should be routinely filed, and records of occupational illnesses and injuries (OSHA Forms 102 and 200) should be maintained. Audits ensuring compliance with the health and safety plan should be carried out.

Proper PPE should be available and properly utilized by all onsite personnel. At each site, the level of PPE required will be determined based on the potential hazards associated with the site and the work activities being conducted.

OSHA has also provided guidance, published in 20 CFR Part 1910.97, for exposure to electromagnetic radiation in the RF region. This guidance states that "for normal environmental conditions and for incident electromagnetic energy of frequencies from 10 MHz to 100 gigahertz (GHz), the radiation protection guide is 10 **mW/cm²** (milliwatt per square centimeter) as averaged over any possible 0.1-hour period. " This means that a power density of 10 **mW/cm²** for periods of 0.1 hour or more or an energy density of 1 **mW-hr/cm²** during any 0.1-hour period should not be exceeded without careful consideration of the reasons for doing so.

2.2 OPERABILITY OF THE TECHNOLOGY

KAI's RFH system is described in Subsection 1.4. The components of an RFH system have three major purposes: heating the soil by applying RF energy to it, collecting vapors released by the heated soil, and treating those vapors. During the SITE demonstration, KAI was subcontracted by B&RE to design and operate the RFH system, but not the vapor collection and vapor treatment systems. B&RE provided project and site management, designed and operated the vapor collection and treatment systems, and assisted KAI in the construction and operation of the RFH system.

Several problems were encountered in the implementation of KAI's RFH system. Start-up was delayed because the chosen frequency required the approval of both the FCC and the Air Force Frequency Manager. This delay may not be expected to occur at all remedial sites. There was also significant downtime after start-up because of problems with the 3-phase AC power transmission system. The instability of the AC power available to the RFH system caused occasional shutdown. The AC power problem also contributed to the need to adjust the RF generator. In addition, it was periodically necessary to discontinue the application of RF energy to allow the borehole liner to cool, although borehole cooling tubes were later installed to minimize this problem.

Operating parameters that affect the performance of the RFH system include treatment temperature and duration of treatment. The treatment temperature determines the rate at which contaminants are volatilized as well as the range of contaminants that will be volatilized. Both the treatment temperature and the duration of treatment influence the final contaminant concentrations. Operating temperature and treatment time are typically selected based on the contaminants of concern and the required cleanup levels. Based on input from USAF; its contractor, B&RE; and the developer, KAI, the SITE Demonstration Plan specified total recoverable petroleum hydrocarbons (TRPH) as the primary contaminant of concern, 150°C as the operating temperature, and approximately 6 weeks as the treatment time. Because of the expected low initial concentrations, decreases of VOCs and SVOCs were listed as secondary objectives.

Just prior to system installation, KAI and B&RE changed the planned operation of the system. They targeted only volatile organics, specifically gasoline-range hydrocarbons, as the contaminants of concern, which allowed KAI to lower the treatment temperature range to 100 to 130°C. (these changes were not reflected in the SITE Demonstration Plan because the SITE Program was not notified until after the demonstration was completed.)

The design and operation of the vapor collection and vapor treatment systems will also affect performance. Factors that can be varied include the number, location, spacing, and design of the extraction wells; the amount of vacuum applied to the vapor collection system; the air flow rate through the vapor collection system; the amount of time for which the vapor collection system is operated (it can be operated after the application of heat to the treatment zone has been discontinued); and the components of the vapor treatment system.

2.3 APPLICABLE WASTES

The RFH technology is potentially capable of remediating soils contaminated with VOCs and SVOCs, including petroleum hydrocarbons. According to KAI, the maximum temperatures that can be sustained are in the 300 to **400°C** range. SVOCs with boiling temperatures below this range are suitable candidates for RFH. Inorganics, metals, and other nonvolatile contaminants will not normally be removed

KAI's RFH technology is best applied to contaminated soil in the vadose zone. If saturated soil is to be remediated by RFH, the treatment zone should be dewatered prior to treatment. If the water table is close to the contaminated soil and the groundwater is also contaminated, it may be difficult to heat the soil without volatilizing contaminants in the groundwater, which can be more effectively treated by another method.

Although the economics of treatment by this technology are not favorable for saturated soils (i.e., the cost of treating saturated soils by this technology exceeds the treatment costs incurred by using other technologies, such as pump and treat), it is applicable to unsaturated soils regardless of moisture content. Theoretically, RF energy preferentially heats polar molecules, and water molecules are strongly polar. As a result, moist soils can provide improved absorption of the RF energy. However, this also means that moist soils will require additional energy, particularly if the target soil temperature is above the boiling point of water. At soil temperatures above **100°C**, chemically-bound water molecules continue to absorb RF energy. The dielectric constant of the soil determines the soil's ability to absorb RF energy directly. Other than the impact of the soil dielectric constant, RFH should be applicable to any soil type.

Soil type will, however, impact the operation of the SVE system. For example, soils containing a large fraction of clay may have low air permeability. Theoretically, RFH may enhance the air permeability of soil by removing moisture from it. Since RFH is a technology designed to enhance SVE

performance, site conditions that limit the effectiveness of SVE will affect the level of enhancement achievable by RFH.

2.4 KEY FEATURES OF THE KAI RFH TECHNOLOGY

KAI's RFH technology is similar to both in situ steam extraction and in situ SVE. In SVE, vacuum blowers induce air flow through the soil, stripping VOCs and SVOCs from it [1]. In steam extraction, steam is injected into the ground to raise the soil temperature and strip VOCs and SVOCs from it [2]. The primary difference between these technologies and RFH is that RFH uses RF energy to heat the soil in the treatment zone. Because the RFH technology uses higher temperatures, it is more aggressive than either steam extraction or SVE. Theoretically, RFH can therefore be applied to less volatile contaminants.

2.5 AVAILABILITY AND TRANSPORTABILITY OF SYSTEM

KAI owns and operates one 25-kW RFH system, which was used for the SITE demonstration. The assembly of this system is a multistep process. The applicators and the installation towers were all shipped as part of the same truck/trailer system that contained the RFH system. The extraction wells, pressure transducer wells (if used), electric field measurement wells (if used), thermowells, and antennae are installed in boreholes. After the subsurface components are installed, above-ground wiring and piping is completed and the vapor collection and treatment systems are connected to the subsurface components.

The assembly of the proposed 200-kW RFH system will be similar to the assembly of the existing 25-kW system. It is projected that the 200-kW system will be transported on four trailers. The system will use more antennae and extraction wells than the pilot-scale system, but the multistep installation process will be the same.

For both pilot-scale and commercial-scale projects, the vapor treatment system will vary from site to site. During the SITE demonstration, the vapor treatment system consisted primarily of a condensate collection system and a propane-fueled flare. The flare was mounted on a trailer, and the condensate collection system was assembled onsite. An air compressor and instrumentation for the vapor treatment system were installed in a small building that was constructed for the demonstration.

2.6 MATERIALS HANDLING REQUIREMENTS

Materials handling requirements prior to treatment are minimal because this is an in situ system. Although not evaluated during this demonstration, KAI claims that soil removed from boreholes during the installation of the electrodes and thermowells may be placed on top of the treatment zone and treated with the undisturbed soil. If the soil cuttings are not treated with the undisturbed soil, they must be treated or disposed of in some other fashion.

Depending on its design, the vapor treatment system may generate residuals. The 'materials handling requirements for these residuals will vary depending on the design of the vapor treatment system and the contaminants present in the soil. During the SITE demonstration, uncondensed vapors were channeled directly to a propane-fueled flare. Vapors that condensed in the vapor treatment system were collected in a 55-gallon drum, and then transferred to the Kelly AFB industrial wastewater treatment facility for treatment and disposal. The residuals generated by the vapor treatment system of a commercial-scale RFH system will depend on the vapor treatment system used and the nature of the site being remediated.

Another aqueous residual generated during the RFH SITE demonstration was the washwater from personnel and equipment decontamination. Commercial applications of the RFH technology will also generate groundwater residuals if dewatering is employed.

2.7 SITE SUPPORT REQUIREMENTS

Remediation using the RFH process will require that certain utilities be available at the site. Water must be available for steam-cleaning the drill rig and auger and for other equipment and personnel decontamination activities. Electrical power must also be available. It is projected that 480-volt, 3-phase power will be needed at an onsite distribution point and that a 3-phase 480- to 240-volt transformer will be needed to establish the required single-phase service. The primary component connected to the 480-volt, 3-phase power will be the RF generator; the majority of the minor system components will use 240-volt, single-phase power.

A mobile drill rig and drill crew will be required onsite for the installation of the subsurface components. Depending upon local regulations, it may also be necessary to remove all subsurface components after treatment, and then redrill and backfill all boreholes. During the SITE demonstration,

it was necessary to redrill all boreholes and backfill them with bentonite at the end of the test. The drill rig will also be used to install dewatering wells, if dewatering is necessary. A fork lift truck and operator will be required during disassembly. Onsite storage requirements include temporary storage for residuals collected from the vapor treatment system (if any), groundwater collected during dewatering (if dewatering is required), and water used in decontamination activities.

2.8 LIMITATIONS OF THE TECHNOLOGY

In general, KAI's RFH technology is not recommended for the remediation of saturated soils. If saturated soil is to be remediated by RFH, the treatment zone should be dewatered prior to treatment. This will add to the total treatment cost and may not be effective, depending on the local hydrogeologic conditions. If the water table is close to the contaminated soil and the groundwater is also contaminated, it may be difficult to heat the soil without volatilizing contaminants in the groundwater which can more effectively be treated by another method.

KAI's RFH system can only be used to remove contaminants that can be volatilized at soil temperatures that the system can practically achieve throughout the treatment zone. This limits the technology to soil contaminated with VOCs and SVOCs, since nonvolatile organics, metals, and inorganics will not normally be removed at temperatures the system can achieve.

Contaminants in silty or clayey soils are usually strongly sorbed and difficult to remove. Clayey soils may also have insufficient air permeability for adequate extraction of vaporized contaminants. Vacuum extraction of vapors from heterogeneous soils may also be difficult. Extraction of vapors from such soils frequently bypasses lower-permeability zones, leaving contaminants behind.

The SITE demonstration provides an example of the application of KAI's RFH system to heterogeneous soil. The demonstration treatment zone included highly permeable zones, containing primarily gravel and sand, as well as less permeable zones, containing a significant percentage of silt and clay. As will be discussed in Section 4, significant residual contamination was measured in the treatment zone after the SITE demonstration. It is not clear, however, whether this indicates a limitation of the system or a problem with the implementation of the system. Because only a portion of the revised treatment zone reached the target temperature range of 100 to 130°C, it is possible that the system was not allowed to operate long enough to achieve an adequate treatment temperature. This was at least partly due to the amount of time available for treatment and problems with the electrical power source. The

design and operation of the SVE system may have also adversely affected contaminant decreases.

As discussed in Subsection 2.2, problems with the 3-phase AC power transmission system led to significant downtime at the beginning of the SITE demonstration. If adequate power is not available at a site, it must be produced by a generator.

2.9 REFERENCES

1. Engineering Bulletin: In Situ Soil Vapor Extraction Treatment. EPA/540/2-91/006, May 1991.
2. Engineering Bulletin: In Situ Steam Extraction Treatment. EPA/540/2-91/005, May 1991.

SECTION 3

ECONOMIC ANALYSIS

3.1 INTRODUCTION

The primary purpose of this economic analysis is to estimate the costs (not including profit) for a commercial-scale system using KAI's in situ RFH technology to remediate 10,940 tons of soil contaminated with volatile and semivolatile organics. This analysis is based upon the results of a SITE demonstration that utilized KAI's pilot-scale RFH system, information from previous tests conducted by KAI, and information obtained from engineering textbooks.

3.2 BASIS OF ECONOMIC ANALYSIS

The cost analysis is typically prepared by breaking down the overall cost into 12 categories. The cost categories, and the areas that each of them generally comprise, are listed below. As presented, not all categories are included in the economic analysis associated with this document.

- | | |
|--|--|
| <ul style="list-style-type: none">• Site preparation<ul style="list-style-type: none">----- site design and layout----- surveys and site logistics----- legal searches----- access rights and roads----- land clearing----- preparations for support and decontamination facilities----- utility connections----- auxiliary buildings• Permitting and regulatory<ul style="list-style-type: none">----- actual permit costs----- system monitoring requirements• Equipment<ul style="list-style-type: none">----- equipment used during treatment----- freight----- sales tax• Startup and fixed<ul style="list-style-type: none">----- transportation of personnel to the site----- wages and living expenses----- assembly of the unit----- shakedown, testing, and training----- working capital----- insurance----- contingencies----- property taxes----- process monitoring equipment----- engineering and supervision | <ul style="list-style-type: none">• Operating costs for treatment<ul style="list-style-type: none">----- labor----- fabrication----- drilling• Supplies<ul style="list-style-type: none">----- spare parts----- bentonite• Consumables<ul style="list-style-type: none">----- electricity----- water----- diesel fuel• Effluent treatment and disposal<ul style="list-style-type: none">----- further treatment/disposal of effluent(s)----- onsite storage of effluent(s)• Residuals and waste shipping, handling, and transport<ul style="list-style-type: none">----- storage of residuals/wastes----- transportation of residuals/wastes----- treatment/disposal of residuals/wastes• Analytical services<ul style="list-style-type: none">----- sampling and analytical program• Facility modification, repair, and replacement<ul style="list-style-type: none">----- maintenance material costs----- design adjustments----- equipment replacements• Site demobilization<ul style="list-style-type: none">----- disassembly costs----- site cleanup and restoration----- wages and living expenses |
|--|--|

3.3 ISSUES AND ASSUMPTIONS

This subsection summarizes the issues and assumptions of the economic analysis for this study. The objective of this SITE demonstration was to treat a single cell having dimensions of 15 feet by 10 feet by 20 feet (111 cubic yards or 171 tons) using a 25-kW system. This economic evaluation was based on the original design of the RFH system for the demonstration. Because of the problems encountered during the demonstration, several assumptions had to be made about the technology. Even though no conclusions about the success of RFH at Kelly AFB can be made, the economic evaluation assumes the technology will meet target cleanup levels within a given timeframe.

For this analysis, the goal was to estimate remediation costs of a full-scale system based upon a site of approximately 10,000 tons at a depth of 20 feet. The size of the full-scale system is estimated to be 200-kW (modular system of eight 25kW generators). Therefore, a factor of eight was used to scale-up the system used in the SITE demonstration to the full-scale level. Desiring to keep the length of the cell at 1.5 times its width, the cell dimensions at the full-scale level would be approximately 42 feet by 28 feet by 20 feet (900 cubic yards or approximately 1,400 tons). Based upon these dimensions, it was determined that the mass of eight cells (10,940 tons) would be the mass used for this analysis since it most nearly met the 10,000 ton goal. The full-scale site is assumed to be 2 cells in length by 4 cells in width. It is assumed the full-scale cleanup will proceed along the width of the site, allowing savings to occur due to the overlapping of extraction well rows. The exact configuration of the full-scale system in each cell is site-specific and is not included in this analysis.

It is assumed that the frequency of operation of the 200-kW unit will be 13.56 MHz. It is also assumed that the RFH system will operate 24 hours per day, 7 days per week with a 95 percent on-line time. Therefore, the total estimated time the equipment will be onsite is 76 weeks.

A utilization factor of 90 percent was assumed. The utilization factor is used to adjust the unit treatment cost to compensate for the fact that the system is not leased to a client at all times because of limited market demand for this type of technology. Through the use of the utilization factor, costs incurred while the system is not leased out are incorporated into the unit cost and distributed evenly to all occasions when the system is applied to a project. Costs that accrue when the system is not in use include insurance, taxes, and capital equipment costs.

The cost of the SVE system is generally a significant part of the RFH treatment costs. Therefore, to estimate the SVE system as a percentage of the treatment costs, it was assumed that the SVE system would incur 50 percent of the following costs:

- Insurance
- Electrical
- Freight
- Tax
- Labor during startup
- Assembly
- Labor during treatment
- Labor during fabrication
- Electricity
- Site demobilization and transportation
- Labor during site demobilization

The primary pieces of equipment of the SVE system used in this cost analysis are PVC pipes for extraction wells and above-grade conduit, and a well junction box.

The following subsections (Subsections 3.3.1 through 3.3.12) describe assumptions that were made in determining project costs for 7 of the 12 cost categories. This analysis does not include cost values for: site preparation; permitting and regulatory; effluent treatment and disposal; residuals and waste shipping, handling, and transport; and sampling and analytical services. Costs for these categories are highly dependent upon site-specific factors, and therefore, no estimates are presented in this economic analysis. Consequently, the actual cleanup costs incurred by the site owner or responsible party may be significantly higher than the costs shown in this analysis. The actual cost is expected to fall between 70 percent and 150 percent of this estimate. This level of accuracy is accepted by the SITE Program as appropriate for generating estimates without the benefit of detailed engineering data [1]. However, since this cost estimate is based on a preliminary design, the range may actually be wider.

According to Plant Design and Economics for Chemical Engineers [2], insurance, property taxes, spare parts, contingency costs, and maintenance materials can be estimated as a percentage of the fixed capital investment required for a project. The components of the fixed capital investment that apply to this project are:

- Total equipment cost applied to the project (including freight and sales tax)
- Supply of spare parts (5 percent of fixed capital investment)
- Transportation (other than freight)
- Assembly
- Shakedown, testing, and training
- Contingencies (10 percent of fixed capital investment)
- Engineering and supervision for system installation

Since some of these components are estimated independently of the fixed capital investment (e.g., assembly), and others are percentages of the fixed capital investment applied to the project (e.g., contingencies), a formula for calculating the fixed capital investment was developed.

The vendor claims that the treatment cost estimate presented in this analysis may be significantly higher than the actual cost since some components of the RFH system used in the SITE demonstration may not be required in the full-scale system. Vendor claims are presented in Appendix C.

3.3.1 Site Preparation

The amount of preliminary site preparation required is highly dependent on the site. Consequently, site preparation costs are not included in this cost estimate and are assumed to be the responsibility of the site owner or responsible party. It is essential to consider that site preparation measures may significantly increase the costs associated with the use of this technology.

3.3.2 Permitting and Regulatory

Permitting and regulatory costs can vary greatly because they are site- and waste-specific. Consequently, no permitting or regulatory costs are included in this analysis. This category may be a significant factor in determining project costs since permitting activities can be both expensive and time consuming.

3.3.3 Equipment

The primary pieces of equipment of the KAIRFH system include:

- RF generator and tuner
- Antennae
- Extraction wells
- Fiberoptic wells and electric field measurement wells
- Vapor barrier
- Vapor collection system
- Vapor treatment system
- Instrumentation
- Electrical

Equipment cost estimates are based on vendor quotes, estimates by B&RE or information provided by Plant Design and Economics for Chemical Engineers [1]. When necessary, the Chemical

Engineering Cost Index [3] is used to estimate current costs from earlier cost data. The annualized cost (rather than depreciation) is used to calculate the annual equipment costs incurred by a site. The annualized cost is calculated using the following formula:

$$A = P \frac{i (1 + i)^n}{(1 + i)^n - 1}$$

where:

- A** = *annualized* cost, \$
- P** = present value principal sum, \$
- i** = interest rate, %
- n** = *years*

The value “n” is the useful life of the RFH unit and equipment (n = 10). It is assumed that a 1-year loan at 8.5 percent interest has been secured to cover the cost of the equipment. The annualized equipment cost prorated to the actual time the unit is at the remedial site (including assembly, shakedown and testing, treatment, and disassembly) is \$332,268 over a period of 76 weeks (1.46 years). The unit is assumed to have no salvage value.

The list prices of the RF generator and tuners are estimated to be \$836,000. The prices for the antennae and extraction wells were determined from a standard engineering reference [2] and are estimated to be \$168,449 and \$7,618, respectively. The developer states that full-scale commercial systems would utilize less-expensive temperature measuring instruments, such as thermocouples. Consequently, the use of thermocouples has been assumed for this estimate. Thermocouple well prices were based upon information from instrument and plastics catalogs [4][5] and are estimated to be \$11,081.

The price of the vapor barrier system, as provided by a silicon rubber sheet manufacturer, is estimated to be \$392. This process requires two vapor collection systems, the prices of which are estimated to be \$4,704 each, based upon prices obtained from a parts catalog [6]. The process also requires a vapor treatment system; however, the system is considered to be a site-specific cost since it is dependent on the contaminants present and local regulations. Therefore, the cost for the vapor treatment system is not included in this cost estimate. Instrumentation for the system is assumed to be 13 percent of the purchased equipment cost and estimated to be \$174,394 for the project [2]. Electrical costs are assumed to be 10 percent of the purchased equipment cost and estimated to be \$134,149 for the project.

Freight costs are assumed to be 6 percent of the total equipment purchase cost and estimated to be \$80,489 for the project [2]. Sales taxes are assumed to be 5.5 percent of the total equipment purchase cost and estimated to be \$73,782 for the project. When these costs are added to the total equipment purchase cost, the overall equipment cost is estimated to be \$1,341,490.

3.3.4 Startup and Fixed

Transportation activities include moving the KAI RFH system to the site. Travel costs for equipment are covered under the freight charge applied to the total equipment purchase cost discussed in Subsection 3.3.3.

Assembly consists of unloading the system from the trailer and assembling it at the site. It is assumed that one fork lift truck at \$325 per hour and one operator at \$25 per hour will be required. The cost to transport the fork lift truck to and from the site is \$55 per hour, and it is assumed that it will take 4 hours to drop off and pick up the forklift. The total assembly cost is estimated to be \$1,545.

It is estimated that 3 weeks will be required to set up equipment onsite, install antennae, extraction wells, and thermocouples, and 1 week to assemble the above-ground components of the system. Assembly and shakedown and testing are assumed to require five workers (two junior electricians, one senior electrician, one technician, and one project manager). The assembly will consist of two 2-person crews for 12 hours per day each; two-man crews were chosen since it is common practice at Superfund sites to enact the “buddy system.” The first shift will consist of a junior electrician and the technician, and the second shift will consist of a junior electrician and the senior electrician. It is estimated the project manager will spend 50 percent of his or her time on the project during assembly. Workers are assumed to be local or will maintain residence near the site and will not be paid for travel or living expenses. However, to compensate for the lack of living expenses, each worker’s salary was increased by a factor of 1.33. A multiplier of 1.8 was used for each of the worker’s salaries to cover benefits and other overhead costs. The estimated labor cost for assembly is \$91,413. Listed below are the fully-burdened costs (including wages, benefits, overhead, and profit) for all onsite personnel involved with assembly and all other phases of the project.

- Junior Electrician — \$99,000/year
- Senior Electrician — \$135,000/year
- Technician — \$108,000/year
- Project Manager — \$162,000/year

Working capital consists of the costs of borrowing capital for supplies, utilities, spare parts, and labor necessary to keep the RFH system operating without interruption due to financial constraints [2]. The working capital for this system is based on maintaining 2 months of payroll for labor, 2 months of payroll for the drilling subcontractor, and 1 month of inventory of the other items. For the calculation of working capital, 1 month is defined as one-twelfth of 1 year. The estimated required working capital is \$103,043. The working capital cost at 8.5 percent interest for the time the equipment is onsite is \$13,590. Therefore, the total working capital cost is \$116,633.

Insurance is assumed to be 2 percent of the fixed capital investment and estimated to be \$33,752 per year and \$54,660 for the project. Property taxes are assumed to be 3 percent of the total fixed capital investment [5] and are estimated to be \$50,628 per year and \$81,990 for the project.

The cost for the initiation of process monitoring programs has not been included in this estimate. Depending on the site, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring requirements may have a significant impact on the project costs. Air monitoring is likely to be required due to the potential release of air emissions during treatment.

A contingency cost is included to cover additional costs caused by unforeseen or unpredictable events, such as strikes, storms, floods, and price variations [2]. The project contingency cost is estimated to be 10 percent of the fixed capital investment. The annual contingency cost is \$168,851 for a cost of \$184,579 to the project.

3.3.5 Operating Costs for Treatment

Treatment operations for the RFH system will be conducted 24 hours per day, 7 days per week for 51 weeks. It is assumed that energy will be applied to each cell for a total of 6 weeks (same duration that energy was applied during the SITE demonstration). It is estimated that it will take 3 weeks for each cell to cool down. However, the time required to cool down will only add 3 weeks to the total time onsite for the last cell, since all of the duplicated components can be removed during cool-down. It is also assumed that it will take one week to move from one cell to the next. Labor costs consist of fully-burdened personnel costs for five workers. Fully-burdened personnel costs are provided in Subsection 3.3.4. The treatment labor force will be structured as described in Section 3.3.4. The total labor cost for treatment is estimated to be \$732,302.

It will be necessary to subcontract a drilling company for the installation and removal of the electrodes and thermowells. A two-person crew will operate the drill rig. Boreholes for extraction wells, antennae, electric field wells, and thermowells are assumed to be drilled to a depth of 20 feet. The cost for drilling a 10-inch-diameter hole with a hollow stem auger is assumed to be \$18 per foot. The estimated costs for installing and removing the extraction wells and antennae are \$6.50 and \$2.50 per foot, respectively. The total drilling costs for the project are estimated to be \$1,161,020.

3.3.6 Supplies

For this project, supplies consist of spare parts and bentonite for backfilling the boreholes after the extraction wells and antennae are installed. Annual spare parts costs are estimated to be 5 percent of the fixed capital investment [2], which is approximately \$84,379 per year and \$122,986 for the entire project,

Bentonite used to backfill the boreholes after the extraction wells and antennae are installed is assumed to cost \$12 per bag with each bag containing 50 pounds of bentonite chips. It is estimated that 13,744 bags of bentonite will be required for the project at a total cost of \$164,394.

3.3.7 Consumables

Electricity is required not only during the heating of the cell but also during its cool-down period. The average hourly power usage rates during the heating and cool-down periods are estimated to be 484.5 kW and 84.5 kW, respectively. Based on a 6-week duration for heating a cell and 3-week duration for a cooling period for each cell, the total electricity cost for the project is approximately \$327,074 (at a rate of \$0.077 kWh).

In order to implement the KAI RFH technology, the site must have a supply of uncontaminated water available. Water will be used for decontamination of the drill rig augers and be added to the bentonite used in backfilling the boreholes and is estimated to be 600 gallons per day. A sewerage charge is also assumed for all water used even if it is not discharged to the sewer. Based upon rates provided by the Cincinnati Water Works, the total water and sewerage bill for the project is estimated to be \$985.

3.3.8 Effluent Treatment and Disposal

Steam and vaporized contaminants will be given off during treatment using the RFH system. Entrained liquid may also be present in the effluent stream. This vapor stream should be the only effluent from the system. A vapor treatment system may be operated in series with the RFH system. The design of this vapor treatment system will vary depending on the contaminants present in the soil. Therefore, for the purposes of this report, this site-specific cost is assumed to be the obligation of the site owner or responsible party and is not included in this analysis.

3.3.9 Residuals and Waste Shipping, Handling, and Transport

If the treatment area extends below the natural water table, it will be necessary to install dewatering wells to lower the water table. The groundwater pumped out of these dewatering wells is likely to be contaminated. However, because dewatering will only be required at some sites and because the quantity of groundwater removed and the contaminants present in the groundwater will vary from site to site, this site-specific cost is assumed to be the obligation of the site owner or responsible party and thus is not included in this estimate.

Several boreholes will be drilled for installation of the extraction wells and antennae. The soil cuttings removed from these boreholes will be contaminated and will require treatment. During the demonstration, these cuttings were drummed for later disposal. For this cost estimate, it is assumed that the cuttings will be placed on top of the soil surface and treated along with the undisturbed soil. If the cuttings are not treated along with the undisturbed soil, they will be a contaminated residual. The residual treatment cost is also assumed to be the obligation of the site owner or responsible party and is not included in this estimate.

3.3.10 Analytical Services

No analytical costs are included in this cost estimate. The responsible party may elect or may be required by local authorities to initiate a sampling and analytical program at its own expense. If specific sampling and monitoring criteria are imposed by local authorities, these analytical requirements may contribute significantly to the cost of the project.

3.3.11 Facility Modification, Repair, and Replacement

Maintenance costs vary with the nature of the waste and the performance of the equipment and include costs for design adjustments, facility modifications, and equipment replacements. For estimating purposes, annualized maintenance costs (excluding labor) are assumed to be 3 percent of the fixed capital investment [2] and are estimated to be \$50,655 per year and \$55,374 for the project.

3.3.12 Site Demobilization

It is assumed that the transportation costs in the demobilization phase will be equal to the transportation costs of the assembly phase of the project. Therefore, the cost for site demobilization is estimated to be \$10,820. It is assumed that 1 week will be required for disassembly of the above-ground components and 1 week will be required for preparation time needed to remove the equipment from the site. Labor will be structured as described in Subsection 3.3.4 and will cost approximately \$159,775.

3.4 RESULTS OF ECONOMIC ANALYSIS

This subsection summarizes the results of the economic analysis of the KAI RFH system treating 10,940 tons of soil based upon the developer's claim that the RFH system is capable of operating with an on-line factor of 95 percent on a full-scale level. The on-line factor is used to adjust the unit treatment cost to compensate for the fact that the system is not on-line constantly because of maintenance requirements, breakdowns, and unforeseeable delays, and considers costs incurred while the system is not operating.

Table 4 summarizes the estimated treatment costs per ton using the KAI RFH system in the treatment of 10,940 tons of soil with an on-line percentage of 95 percent. Table 4 also presents the treatment costs of the 12 cost categories as a percentage of the total cost. It is important to remember that the five cost categories not included in this analysis may significantly add to the unit cost. These costs are considered order-of-magnitude estimates as defined by the American Association of Cost Engineers. The actual cost based upon EPA's evaluation is expected to fall between 70 and 150 percent of the estimated cost. The vendor claims the cost may be as low as 50 percent of the cost indicated in Table 4.

Table 4. Treatment Costs for the KAI RFH System Treating 10,940 Tons of Soil with a 95 Percent On-line Time

Item	Cost (\$/ton)	Cost (as a % of total cost)
Site preparation	NE	NE
Permitting and regulatory	NE	NE
Equipment	30.37	9.0
Startup and fixed	54.13	16.1
Operating costs for treatment	173.06	51.5
Supplies	26.32	7.8
Consumables	30.02	8.9
Effluent treatment and disposal	NE	NE
Residuals and waste shipping, handling, and transport	N-E	NE
Analytical	NE	NE
Facility modification, repair, and replacement	6.74	2.0
Site demobilization	15.59	4.6
Total operating costs	336.24^a	100^b

a Approximately \$50 per ton of the total cost is attributed to the SVE system.

b The SVE system is approximately 15% of the total cost.

NE = Not estimated in the analysis. The cost for this item is highly dependent on site-specific factors.

Table 4 indicates that the RFH system will cost approximately \$336 per ton to remediate the 10,940-ton site. Table 4 also illustrates that startup and fixed and operating costs for treatment contributed the most to the unit cost, and labor is approximately 27 percent of the total cost. SAIC estimates that the SVE system is responsible for approximately \$50 per ton of the treatment costs (15% of the total cost)[7].

3.5 REFERENCES

1. Evans, G.M. Estimating Innovative Technology Costs for the SITE Program. Journal of the Air and Waste Management Association, Vol. 40, No. 7, July 1990. pp. 1047-1051.
2. Peters, M.S. and K.D. Timmerhaus. Plant Design and Economics for Chemical Engineers, Third Edition. McGraw-Hill, Inc., New York, 1980.
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SECTION 4

TREATMENT EFFECTIVENESS

4.1 BACKGROUND

The SITE demonstration of KAI's RFH system took place at Site S-1 at Kelly APB near San Antonio, Texas (see Figure 2). From 1960 to 1973, Site S-1 was used as an intermediate storage area for wastes awaiting offsite reclamation. Waste liquids including mixed solvents, carbon cleaning compounds, petroleum oils, and lubricants were temporarily stored in tanks located within this area. Spills during waste transfer operations and flooding of storage tanks are reported to have caused the current soil contamination. Much of the spilled waste accumulated in a long sausage-shaped "sump," which was the lowest portion of a depression on the eastern side of the site. After waste transfer operations at the site were halted, the tanks were removed, the sump and depression were backfilled, and the area was graded. Soil contamination persists down to the saturation zone, which begins approximately 25 to 30 feet below the surface.

Figure 3 shows the locations of the depression and the sausage-shaped sump. The SITE demonstration was conducted in the southern end of the sump, where preliminary sampling indicated that contaminant concentrations were highest. The original treatment zone, as specified in the Demonstration Plan, was 10 feet wide, 15 feet long, and 20 feet deep. The original plan specified that the 10-foot applicators would be moved up and down in their liners, applying heat from 0 to 20 feet below ground surface (bgs). However, before the RFH system was turned on, B&RE and KAI made the decision to apply heat to only half of the original treatment zone. The "revised treatment zone" is 10 feet wide and 15 feet long but only extends from 4 to 14 feet bgs. The depth was reduced because the applicators remained stationary in their liners. All of these modifications were made based on timing and funding limitations placed on the project just prior to startup. The SITE Program was not informed of any of these changes until after sampling was completed; therefore, no changes to the Demonstration Plan were made.

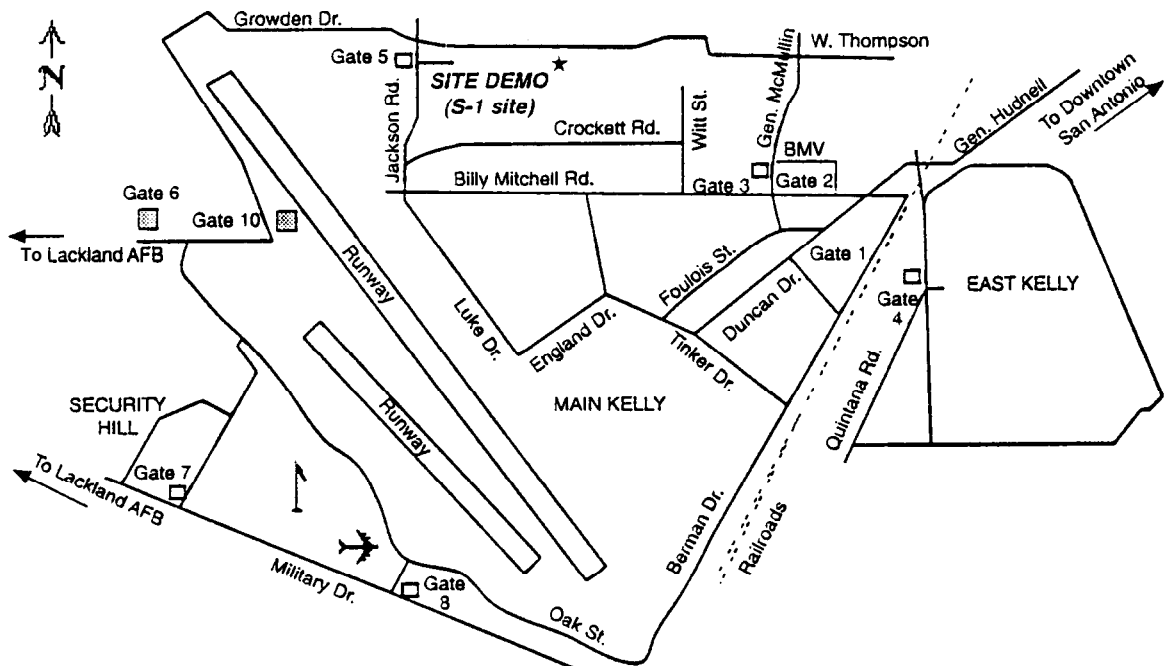
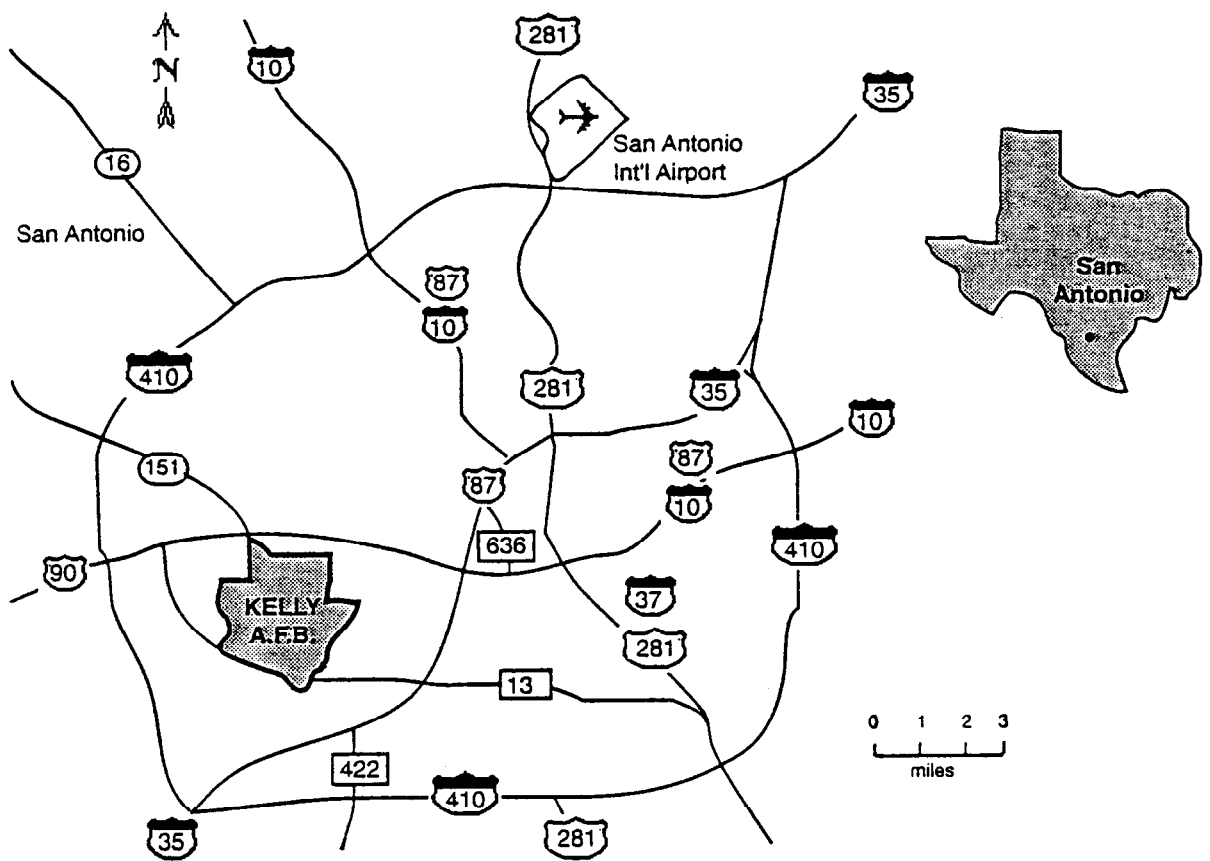


Figure 2. Regional maps showing demonstration location.

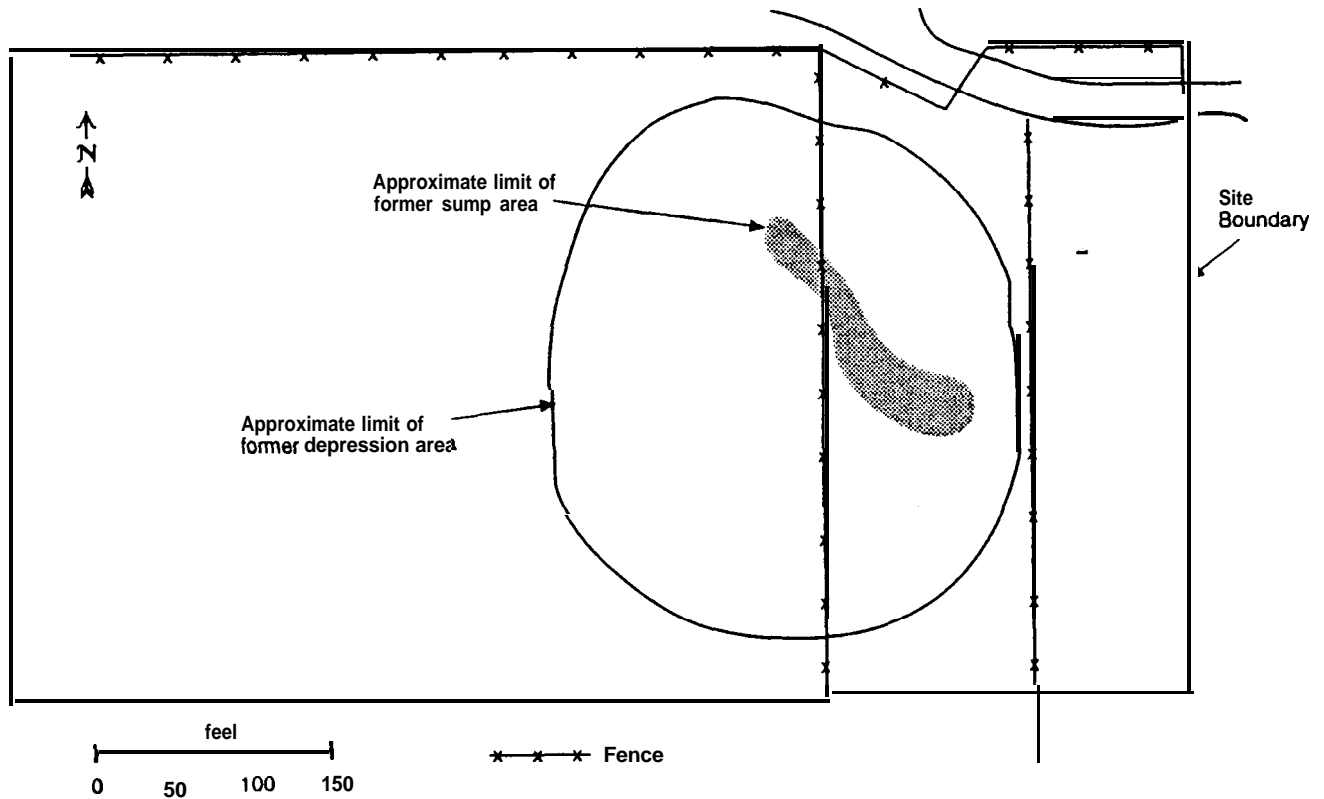


Figure 3. Plan view of demonstration site.

During the demonstration, power was supplied alternately to the two antennae, A1 and A2. Power was applied to A2 for 28.9 days, then switched to A1. After the A1 heating commenced, a high voltage discharge occurred within the transmission line near it. The center conductor heated beyond the system's thermal expansion capability and shorted A1, so power was only applied to A1 for 8.2 days.

Heating was switched back to A2 for the final 12.9 days. This malfunction caused the soil surrounding the A1 liner to be heated to a significantly lesser degree than the soil surrounding the A2 liner.

The primary objective of the SITE Program demonstration was to evaluate the ability of the RFH system and associated SVE system to remove TRPH from the soil. In addition to the SITE Program's primary objective, the following secondary objectives were developed:

1. Evaluate the removal of VOCs feasible under the conditions of the test. Target VOCs are listed in Table 5.

2. Evaluate the removal of SVOCs feasible under the conditions of the test. Target SVOCs are listed in Tables 6 and 7.
3. Determine the outward migration, if any, of contaminants into a zone outside the treatment area.
4. Characterize the soil being treated by determining particle size distribution.

After a review of data from another RFH demonstration conducted at the same site, the following additional secondary objectives were added as part of the demonstration:

1. Characterize the vapors extracted by the SVE system by collecting vapor samples at six key times before, during, and after the operation of the RFH system.
2. Characterize the soil vapor at the site by collecting soil gas samples before treating the soil.
3. Characterize the groundwater at the site and identify if the groundwater could be a potential source of contaminant migration into the treatment zones by collecting groundwater samples from existing wells.

Table 5. Target VOCs

Acetone	Benzene	Bromodichlorobenzene
Bromoform	Bromomethane	2-Butanone
Carbon disulfide	Carbon tetrachloride	Chlorobenzene
Chlorodibromomethane	Chloroethane	2-Chloroethyl vinyl ether
chloroform	Chloromethane	1, 1-Dichloroethane
1,2-Dichloroethane	1, 1-Dichloroethene	trans-1,2-Dichloroethene
1,2-Dichloropropane	cis-1,3-Dichloropropane	trans-1,3-Dichloropropene
Ethylbenzene	2-Hexanone	Methylene chloride
4-Methyl-2-pentanone (MIBK)	Styrene	1,1,2,2-Tetrachloroethane
Tetrachloroethene	Toluene	1, 1, 1-Trichloroethane
1,1,2-Trichloroethane	Trichloroethene	Vinyl acetate
Vinyl chloride	Xylenes, total	

Table 6. Target SVOCs (Acid Extractables)

Benzoic acid	4-Chloro-3-methylphenol	2-Chlorophenol
2,4-Dichlorophenol	2,4-Dimethylphenol	4,6-Dinitro-2-methylphenol
2,4-Dinitrophenol	2-Methylphenol	4-Methylphenol
2-Nitrophenol	4-Nitrophenol	Pentachlorophenol
Phenol	2,4,5-Trichlorophenol	2,4,6-Trichlorophenol

Table 7. Target SVOCs (Base/Neutral Extractables)

Acenaphthene	Acenaphthylene	Anthracene
Benzo(a)anthracene	Benzo(b)fluoranthene	Benzo(k)fluoranthene
Benzo(ghi)perylene	Benzo(a)pyrene	Benzyl alcohol
bis(2-Chloroethoxy)methane	bis(2-Chloroethyl)ether	bis(2-Chloroisopropyl)ether
bis(2-Ethylhexyl)phthalate	4-Bromophenyl phenyl ether	Butyl benzyl phthalate
4-Chloroaniline	2Chloronaphthalene	4-Chlorophenyl phenyl ether
Chrysene	Dibenz(a,h)anthracene	Dibenzofuran
Di-n-butylphthalate	1,2-Dichlorobenzene	1,3-Dichlorobenzene
1,4-Dichlorobenzene	3,3'-Dichlorobenzidine	Diethylphthalate
Dimethylphthalate	2,4-Dinitrotoluene	2,6-Dinitrotoluene
Di-n-octyl phthalate	Fluoranthene	Fluorene
Hexachlorobenzene	Hexachlorobutadiene	Hexachlorocyclopentadiene
Hexachloroethane	Indeno(1,2,3-cd)pyrene	Isophorone
2-Methylnaphthalene	Naphthalene	2-Nitroaniline
3-Nitroaniline	4-Nitroaniline	Nitrobenzene
n-Nitrosodiphenylamine	n-Nitrosodipropylamine	Phenanthrene
Pyrene	1,2,4-Trichlorobenzene	

The first step of the data evaluation process was to determine which contaminants were present in a sufficient number of pretreatment samples at sufficient concentrations to warrant a statistical evaluation. Many analytical method-specific VOCs and SVOCs were not detected in any pretreatment samples. The process used to select contaminants for the statistical evaluation is described in Appendix A.

Changes in concentrations were determined for each compound by comparing analytical data generated from soil samples taken before and after the RFH treatment. Initial and final soil samples were taken from “matched” boreholes (i.e., final boreholes were placed as close as possible to the original boreholes and samples were collected from the same depth). Initial and final contaminant concentrations were compared to determine a concentration change for each matched pair. Concentration changes for all matched pairs within a specified zone were used to calculate the geometric mean concentration change for that zone (the geometric mean was used because it was determined that TRPH concentrations were log-normally distributed). The matched pairs of initial and final contaminant concentrations were analyzed using a paired *t* test, which determined whether the geometric mean concentration change within a specific zone was statistically significant. A description and application of the paired *t* test is presented in Appendix A.

B&RE also evaluated KAI’s RFH system in terms of operational features such as performance of the vapor barrier, performance of the vapor collection system, amount of heat lost to the soil surrounding the treatment zone, and measurement of RF fields radiated from the test array. Because these operational features are not central to the SITE demonstration, data collected by B&RE are not presented in Appendix A.

4.2 METHODOLOGY

4.2.1 Soil

Pretreatment soil sampling was conducted concurrent with the installation of the subsurface components. A mobile, hollow-stem auger drill rig was used to drill the boreholes required for the installation of the subsurface components. Figure 1 shows the locations of all subsurface components. The drill rig was also used to drive a split spoon into the boreholes wherever a soil sample was needed. Sampling procedures are described in greater detail in following paragraphs.

The Demonstration Plan specified the collection of samples for TRPH, VOC, and SVOC analyses at the depths and locations shown in Figure 4. Pretreatment soil samples were generally collected at the designated depths, but in a few cases, insufficient soil was recovered in the split spoon at the specified depth. When insufficient recovery was obtained, the next deeper interval was sampled instead. Samples were labeled with ID numbers that identified their locations (borehole and sampling interval).

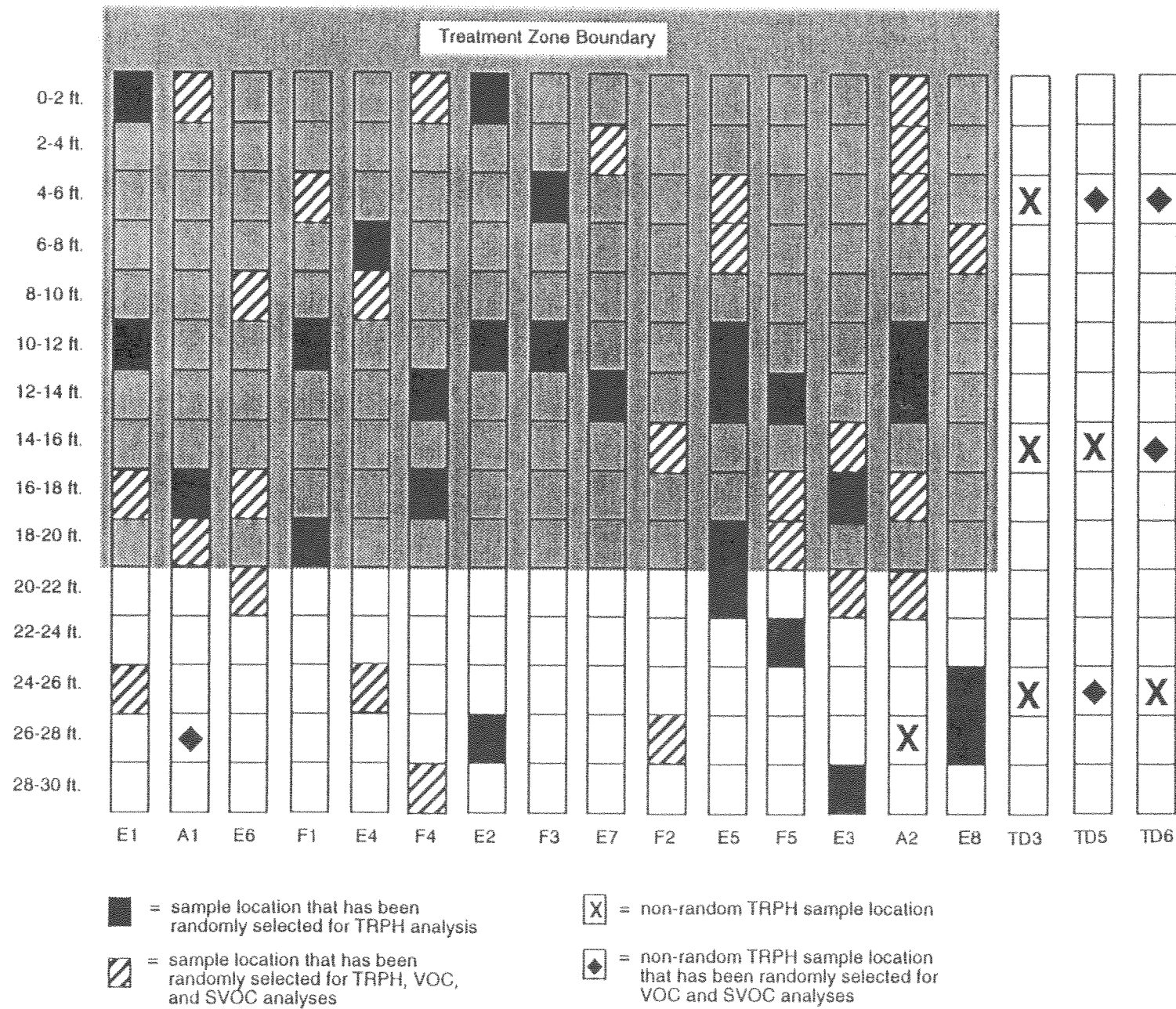


Figure 4 Sampling depths and locations.

RFH began on April 24, 1994 and ended on June 7, 1994. Electrical power supply problems experienced at the beginning of the heating period reduced the amount of RF energy applied to the soil. The vapor collection system was operated from April 13, 1994 until June 24, 1994 to enhance the removal of contaminant vapors. The soil was then allowed to cool undisturbed until July 7, 1994, when final sampling began. The above-ground components of the system were disassembled and removed prior to final sampling. Subsurface components were removed following final sampling.

Post-treatment boreholes were placed within 2 feet of the corresponding pretreatment boreholes. An attempt was made to obtain all post-treatment samples from the same depth as the corresponding pretreatment sample, but insufficient material was collected from one sampling point, and it was necessary to collect that sample 2 feet deeper than planned. All other post-treatment samples were collected at approximately the same depths as the corresponding pretreatment samples.

Soil samples were collected using 3-inch-diameter split spoons. The split spoon was pushed or hammered into the soil (at the appropriate location and depth) using the drill rig. The split spoon was then removed from the borehole and placed on a flat surface covered with clean aluminum foil. The main portion of each split spoon was 2.0 or 2.5 feet long and contained four or five 6-inch-long stainless steel liners, which were numbered from bottom to top. The bottom portion of the split spoon, which was approximately 3 inches long and was called the “shoe,” did not contain any liners.

The soil characteristics at each sampling point affected the number of liners that were filled with soil. The split spoon filled from the bottom: first the shoe filled, then the first liner, then the second liner, and so on. For example, if the split spoon was pushed into the soil 12 inches, and then hit a large rock that stopped its progress, only the shoe and the first liner would have been filled with soil. The second liner would have been partially filled with soil. For each given sampling point, one to four liners were filled with soil.

Soil samples were collected for both chemical and particle size analyses. When a soil sample was selected for chemical analyses, the field sampling crew did not remove it from the stainless steel liner in which it was collected. The ends of the liner were securely covered with Teflon sheets and polyethylene caps. The liner was labeled, sealed in a plastic bag, and placed in a cooler with ice for preservation. When a soil sample was selected for particle size analysis, the field sampling crew removed the sample from its liner and placed it in a plastic jar or a plastic bag. When rocks were present in the sample, extra

material (from the shoe or from other liners) was frequently added to the particle size sample, since larger quantities of material are required for particle size analyses of soils containing large particles. Samples selected for particle size analyses did not require preservation.

When the split-spoon was filled or nearly filled (i.e., three or four liners were full of soil) the second liner was selected for chemical analysis. The third liner was generally selected for particle size analysis. When a chemical analysis field duplicate was collected, the third liner was then used as the chemical analysis field duplicate and the first liner was the particle size sample. When a particle size analysis field duplicate was collected, the first and third liners were the particle size duplicate and sample. When field duplicates for both chemical and particle size analyses were collected from the same split spoon, the second liner was the sample for chemical analysis, the third liner was then used as the field duplicate for chemical analysis, and the first and fourth liners were the particle size sample and duplicate.

When only two liners were full of soil, the second liner was selected for chemical analyses. When a chemical analyses field duplicate was collected, the first liner was selected as the chemical analyses field duplicate, and material from the shoe and any material from the third liner was selected for particle size analysis. When the sampling location was not designated for the collection of a field duplicate for chemical analyses, the first liner was selected as the particle size sample.

When only the first liner was full of soil, it was selected for chemical analyses. Material from the shoe and any material in the second liner was selected for particle size analysis. No field duplicates were collected if only the first liner was full.

Samples, blanks, and QA/QC samples were collected and prepared for chemical analyses. The samples and blanks described in this paragraph were prepared during each phase of sampling (pretreatment and post-treatment). For each phase of sampling, 64 samples were analyzed for TRPH and moisture; 32 of those samples were also analyzed for VOCs and SVOCs. Within the original treatment zone, 40 samples were analyzed for TRPH and moisture; 20 of these samples were also analyzed for VOCs and SVOCs. Within the revised treatment zone, 20 samples were analyzed for TRPH and moisture; 7 of these samples were also analyzed for VOCs and SVOCs.

Also during each phase of sampling, six field duplicates were collected for TRPH and moisture; three of those field duplicates were also analyzed for VOCs and SVOCs. Five laboratory duplicates were prepared for moisture during the pretreatment sample analysis and four during the post-treatment analyses. Four laboratory duplicates were prepared for **TRPH** during each phase of testing. Samples were analyzed for VOCs, SVOCs, and TRPH as matrix spike/matrix spike duplicate (MS/MSD) samples at the frequencies specified in Table 8. Three field blanks were analyzed for VOCs, SVOCs, and TRPH. Each cooler used to ship samples for VOC analyses contained a trip blank, which was analyzed for VOCs.

Additional samples were collected for particle size analysis. During pretreatment sampling, 58 samples and 5 field duplicates were submitted for particle size analysis. During post-treatment sampling, 52 samples and 6 field duplicates were submitted for particle size analysis. One particle size analysis laboratory duplicate was prepared for each phase of sampling. The numbers and types of samples analyzed for the KAI RFH SITE demonstration are summarized in Table 8.

Table 8. Summary of Number of Samples Analyzed for the KAI RFH Test

Measurement	Number of Samples	Field Duplicates	Laboratory Duplicates	Matrix Spikes	Matrix Spike Duplicates	Field Blanks	Trip Blanks	Total
<u>Pretreatment</u>								
TRPH	64	6	4	7	7	3	NA	91
Moisture	64	6	5	NA	NA	3	NA	78
Particle Size Distribution	58	5	1	NA	NA	NA	NA	64
	32	3	NA	5	5	3	10	58
SVOCs	32	3	NA	4	4	3	NA	46
<u>Post-treatment</u>								
TRPH	64	6	4	5	5	3	NA	87
Moisture	64	6	4	NA	NA	3	NA	77
Particle Size Distribution	52	6	1	NA	NA	NA	NA	57
	32	3	NA	5	5	3	6	54
SVOCs	32	3	NA	3	3	3	NA	44

NA = not applicable

4.2.2 SVE Vapor Stream

The SVE system was designed with eight extraction wells. Six of the eight wells (E1, E3, E4, E5, E6, E8) were screened 10 to 20 feet bgs, which is almost entirely below the revised treatment zone of 4 to 14 feet bgs. The other two (E2 and E7) were screened from 0 to 10 feet bgs, which covered all but the last 4 feet in the revised treatment zone. Throughout the demonstration, the SVE system operated using various combinations of extraction wells. At least one extraction well was operating at any given time, and as many as four were used simultaneously. Wells that were not being used at a particular time were capped, with the exception of several days when some wells were open to the atmosphere (i.e., operated in the passive mode). Operating data on the SVE system is presented in Appendix A.

The vapor stream from the SVE system was sampled and analyzed six times during the demonstration. Vapor stream samples were collected from a combined header exhaust port downstream of where the individual extraction wells were tied in. The VOC samples were collected in SUMMA polished stainless steel canisters and analyzed using a gas chromatograph (GC) with dual columns and multiple detectors (GC/MD). The SVOC samples were collected using a modified version of EPA Method 0010 and analyzed using Method 8270. These samples were collected to characterize the compounds being removed from the subsurface during system operation.

4.2.3 Soil Vapor

Six soil vapor samples were collected and analyzed from the existing pressure transducer wells positioned near the treatment area (TD1, TD2, TD3, TD6, TD7, TD8). TD1 and TD2 are deep wells screened from approximately 20 to 24 feet. The others are shallow wells screened from about 10 to 14 feet. The samples were collected in SUMMA polished stainless steel canisters and analyzed for VOCs using GC/MD. These samples were collected prior to the start of RFH and were used to determine what VOCs may have been present in the soil vapor prior to heating. This data is presented in Appendix A.

4.2.4 Groundwater

Groundwater samples were collected from three wells near the treatment zone (MW-10, MW-09, and DW-02) during drilling activities. Three well volumes were purged from each well before the sample was collected. Groundwater samples were analyzed for the same compounds as the soil samples (TRPH, the target VOCs in Table 5, and the target SVOCs in Tables 6 and 7). Data from these samples were used to characterize the groundwater and to identify whether the groundwater was a potential source for

contaminant migration into the treated soil zone

4.3 PERFORMANCE DATA

It is important to note that several operating factors that potentially affected performance were not under the control of the developer. These factors include problems with the delivery of adequate AC power to the RFH system, the placement and screening depths of extraction wells, and the length of time energy was applied to the soil. Commercial application of the RFH technology with these factors under control of the developer may yield significantly different results.

4.3.1 Soil Samples

Soil samples were taken before and after the soil was treated using KAI's RFH technology. As discussed in Subsection 4.2.1, the post-treatment soil samples were taken as close as possible to the pretreatment sampling locations. The analytical data were evaluated as matched pairs of pre- and post-treatment samples. If concentrations had only decreased during treatment, the percent decrease would have been evaluated for each pair. However, in some cases, post-treatment concentrations were higher than pretreatment concentrations. As a result, for each contaminant, the log-transformed ratio of the post-treatment concentration to the pretreatment concentration was calculated for each sample pair. The ratios were evaluated statistically using a *t* test to determine whether the contaminant concentration had exhibited a statistically significant change (starting at the 80 percent confidence level) between the pre- and post-treatment sampling events. The geometric mean ratio of post-treatment concentration to pretreatment concentration was also calculated. This geometric mean ratio was converted to a geometric mean percent decrease or a geometric mean percent increase, as appropriate.

4.3.1.1 TRPH

The soil samples were extracted by EPA Method 9071A [2] prior to TRPH analysis by EPA Method 418.1 [3]. Samples were also analyzed separately for moisture by ASTM Method D2216. The TRPH results were then adjusted to a dry-weight basis. TRPH concentrations exhibited statistically significant changes at the 95 and 90 percent confidence levels within the revised treatment zone and original treatment zone, respectively. The estimated geometric mean decreases were 49 percent within the revised treatment zone and 29 percent within the original treatment zone. Data from pre- and post-treatment TRPH analyses are summarized in Appendix A.

TRPH removals were not as projected. A number of problems with the design and operation of the SVE system were identified after the demonstration was complete. These problems included extraction wells screened below the revised treatment zone, which may have drawn contaminants from the revised treatment zone into the cooler soil, where they condensed. The SVE system configuration also may have resulted in low vapor flows within the treatment zone and in high vapor flows from areas outside the treatment zone. These problems may have resulted in contaminant migration into the treatment zone from surrounding soils. In addition, temperature sensors indicated that only a portion of the revised treatment zone reached the revised target temperature range of 100 to 130°C. The developer claims that the actual soil temperatures were higher than the recorded values since measurements were taken within boreholes. This is due to there being no sensors that measured the instantaneous, microscopic heating of the contaminants, and all sensors were likely to provide readings that were lower than the actual temperatures of materials.

Because of changes in the RFH system prior to startup and the design of the SVE system, it cannot be concluded whether the changes in TRPH concentration inside and outside the treatment zones were a result of RFH treatment or were due solely to application of SVE.

As discussed in Subsection 4.1, significantly more power was applied to A2 than A1 during the demonstration. Because A1 and A2 were heated differently, A1 and A2 zones were evaluated individually in addition to the evaluations of the original and revised zones. Like the revised zone, the A1 and A2 zones both extend from 4 to 14 feet bgs. Because the RFH system heats soil radially, the A1 and A2 zones were elliptically shaped and centered around each antenna. The A1 zone, comprising 15 samples, contains the following boreholes: E1, E6, F1, A1, F4, E4, E2, F3, E7, and E5. The A2 zone, comprising 15 samples, contains the following boreholes: E2, F3, E7, E5, F2, A2, F5, E3, E8, and E4. (See Figure 1 for borehole locations.) The A1 zone did not exhibit a change in contaminant concentration that was statistically significant (at the 80 percent confidence level). The A2 zone exhibited a statistically significant change at the 80 percent confidence level. The estimated geometric mean decrease was 44 percent. Because only a portion of the revised treatment zone reached the target temperature range of 100 to 130°C, it seems most likely that the system did not achieve an adequate temperature. The low temperatures were at least partially due to problems with the electrical power available at the site.

4.3.1.2 SVOCs and VOCs

SVOCs and VOCs were designated as noncritical measurements for this demonstration because samples collected prior to the demonstration indicated that the soil at the site generally contained low concentrations of SVOCs and VOCs. SVOCs and VOCs were designated as noncritical measurements in the Demonstration Plan and therefore their concentrations were measured in only half of the soil samples. SVOC samples were extracted by EPA Method 3540 [2] prior to analysis by EPA Method 8270 [2]. VOC concentrations were determined using EPA Method 8240 [2]. SVOC and VOC results are presented on a dry-weight basis.

Concentrations of individual SVOCs and VOCs in the soil samples were evaluated using the same procedures described for TRPH. Concentrations of several SVOCs exhibited statistically significant changes (at an 80 percent confidence level) within the original and revised treatment zones. Statistically significant changes in SVOC concentrations within the original and revised treatment zones are presented in Table 9. As with the TRPH data, it cannot be concluded that the changes in SVOC concentrations inside and outside the treatment zones were affected by RFH treatment.

Table 9. Summary of SVOC Decreases Inside Treatment Zones

contaminant	Geometric Mean Percent Decrease in Original Treatment Zone	Geometric Mean Percent Decrease in Revised Treatment Zone
Benzo(b)fluoranthene	44 ^a	40 ^b
Benzo(a)pyrene	44 ^c	43 ^b
Bis(2-ethylhexyl)phthalate	55 ^d	***
Chrysene	***	40 ^b
Pyrene	***	60 ^d
Fluoranthene	***	53 ^b

*** No statistically significant change at the 80 percent confidence level.

a Change accepted at a 97.5% confidence level.

b Change accepted at a 80% confidence level.

c Change accepted at a 95% confidence level.

d Change accepted at a 90% confidence level.

Pre- and post-treatment concentrations of individual VOCs were also measured. None of the individual VOCs exhibited statistically significant changes (at an 80 percent confidence level) within the original or revised treatment zones. High concentrations of some VOCs (toluene, chlorobenzene,

methylene chloride) were detected in some soil samples, but the changes in concentrations were not statistically significant. However most target VOCs in the pre- and post-treatment soil samples had low concentrations, and a statistical evaluation could not be made. No conclusions about changes in VOC concentrations can be made.

Due to fewer data points (as compared to amount of TRPH points), and since the analysis of SVOCs and VOCs was not a critical parameter, contaminant changes were not examined in the A1 and A2 zones

4.3.1.3 Particle Size Distribution

Laboratory tests were conducted to determine sample grain size distribution. The full procedure as described in ASTM D422 [2] was used for at least 10 percent of the samples. Samples that were processed in accordance with the ASTM procedure as prescribed are referred to as wet-sieved samples. The remaining samples were analyzed by dry-sieving. Regardless of which procedure was used to perform the grain size distribution, the soils were first prepared according to ASTM Method D421. In this method, the soils are dried and processed to break down all soil particles into their component sizes. Samples processed by dry-sieving were simply taken from this sample preparation procedure and screened using twelve sieve sizes, ranging from 3 inches (7.62 cm) to 75 μm (#200 sieve). For the samples processed by wet-sieving, the dried soil sample is initially segregated into two fractions using a #10 sieve. Soils that pass through the #10 sieve are then dispersed in an aqueous solution and passed over the remaining sieves "wet." Particles that pass the #200 sieve are further classified using a hydrometer, which results in a minimum size classification of approximately 0.001 mm. To provide information required for the reduction of the hydrometer data, the specific gravity of the soils subjected to wet-sieving was determined using the procedure outlined in ASTM D854-83 [1].

This combined use of dry- and wet-sieving was specified in the Demonstration Plan because discussions with laboratory personnel indicated that the two procedures should yield similar results for particle sizes not passing the #200 sieve. This was not the case for the soil samples associated with this site. The dry-sieve method produced results that overestimated the sand fraction of the soil. The soil preparation method was apparently insufficient to break down clumps of cohesive clay particles. It was known that wet-sieving and subsequent hydrometer testing would be required to characterize particles that passed the #200 sieve further and, therefore, a decision was made to subject a subset of the entire sample set to the wet-sieving procedure. Since dry-sieving is less costly, and the further characterization of these

small particles was a minor point, it seemed reasonable to use dry-sieving primarily.

As a result, particle size distribution data obtained by wet-sieving is being used to characterize the site, and the data obtained by dry-sieving are not being used. The particle size distribution summary from wet-sieving tests is listed in Table 10. For evaluation purposes, the data were simplified into three standard geologic categories: gravel, sand, and fines. Particles that are less than 3 inches in diameter but will not pass through a #4 sieve (4.75 mm) are classified as gravel, particles that will pass through a #4 sieve but will not pass through a #200 sieve are classified as sand, and particles that will pass through a #200 sieve are classified as fines. Additional particle size distribution data are presented in Appendix A.

Table 10. Average Particle Size Distribution (Wet-Sieving Only)

	Average Percent Gravel	Average Percent Sand	Average Percent Fines
Pretreatment	29.4	30.7	39.9
Post-treatment	42.9	29.1	28.1

The data show a predominance of sand and gravel at this site, which indicates the soil should be amenable to RFH and SVE.

4.3.2 SVE Vapor Stream

Appendix A lists the results of the vapor stream samples. Approximately 70 VOCs and 12 SVOCs were detected in these vapor samples, indicating that these contaminants were removed from the soil. Typically, vapor stream concentrations from SVE systems are higher when the system is first started, then decreases as the system continues to operate. Because RFH volatilizes the contaminants as it operates, this type of pattern should not be observed. In fact, vapor stream concentrations may increase as the soil temperature increases. In particular, if an area of high contaminant concentration is heated, corresponding increases in the vapor stream concentrations are expected.

During the demonstration, numerous changes were made to the operation of the SVE system. Over the course of the demonstration, the SVE system was operated using 55 different combinations of operating parameters. Operating parameters that were varied included the number of wells being operated

as extraction wells, the number of wells being operated as passive vent wells (if any), and the operating pressure.

The first sample was collected when the SVE system was operational, but prior to the start of the RFH system. Although the SVE system was not yet operating continuously, it was operating for this sampling event. This sample established baseline conditions (i.e., removal with SVE only). Sample 2 was collected just after the RFH system was turned on. Sample 3 was collected when soil temperatures were approximately **100°C** near the operating antenna. (At **100°C**, moisture in the soil should begin to be driven off.) Sample 4 was collected when soil temperatures reached their maximum. Sample 5 was collected several days after the RFH system was turned off, but while the SVE system continued to operate. The sample represented the start of the cool-down phase. Sample 6 was collected just prior to the shut-off of the SVE system.

In general, contaminant concentrations in the first and second vapor samples were almost equal to one another. The third and fourth samples had lower contaminant concentrations than the first two samples. The fifth sample had the lowest concentrations of the six samples, while the last sample had the highest concentrations. These relative concentrations do not match the patterns that would be expected for an SVE system or an SVE system used with an RFH system. However, because the operation of the SVE system varied considerably throughout the demonstration (e.g., wells E4 and E5 were used for vapor extraction for the third and fourth sample, but not the fifth), it is not possible to explain the observed vapor stream contaminant concentrations. The data indicate the SVE system is removing contaminants; however, it is not possible to determine how RFH enhanced SVE performance.

4.3.3 Soil Vapor Gas

These samples were collected on the same day that the baseline sample for the SVE vapor stream was collected (Sample 1). Appendix A lists the results of the soil vapor samples. The soil vapor data appear similar to the vapor stream data from the SVE system (i.e., compounds detected in the soil vapor were also detected in the SVE vapor stream). Because the SVE system operated under varying conditions, no attempt was made to correlate these data sets.

4.3.4 Groundwater Samples

Groundwater was sampled from three different wells just outside the treatment zone before it received RFH. The results of this sampling are listed in Appendix A. The groundwater data, which are considered noncritical, show concentrations of TRPH and several target VOCs and SVOCs. All of these compounds were also detected in either the soil, soil vapor and/or the SVE vapor stream. No attempt was made to correlate these data sets to each other. The approximate location of the wells is displayed in Figure 5.

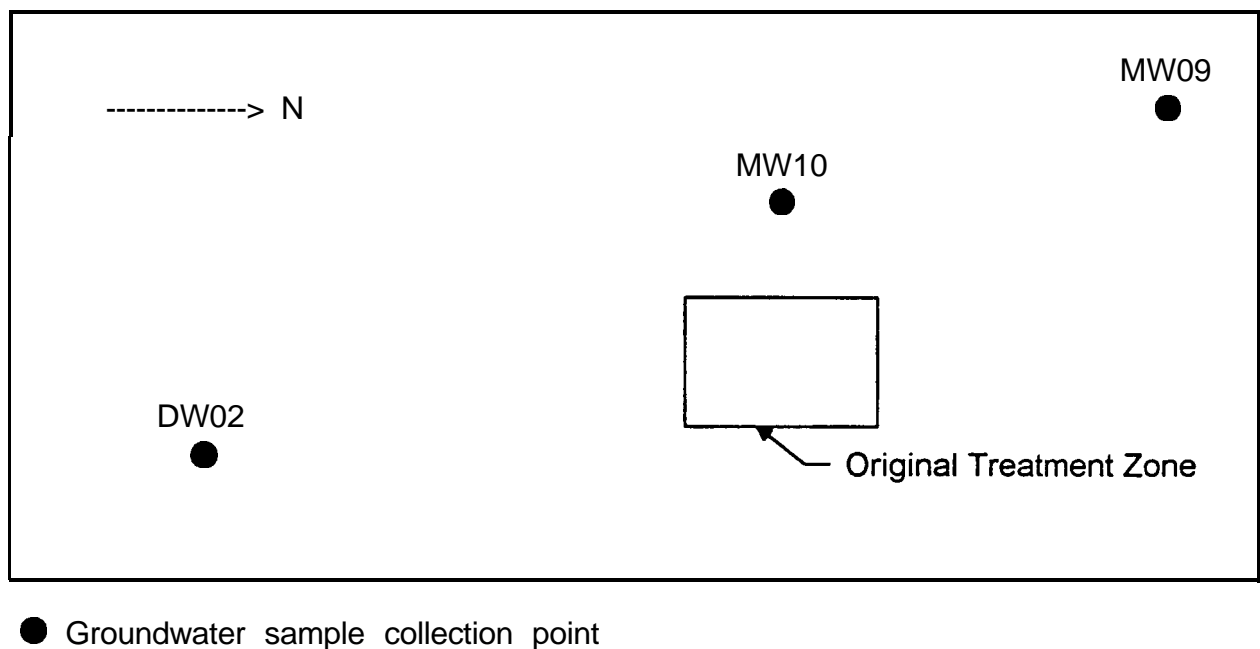


Figure 5. Locations of Groundwater Sample Collection

4.3.5 Moisture

Moisture analysis was conducted so that soil sample concentration results could be converted to dry weight. Appendix A presents the results of moisture analyses.

4.4 CONTAMINANT MIGRATION

An RFH system generates a flow of contaminant vapors in the soil that must be collected with an **SVE** system. A properly designed SVE system will collect the contaminant vapors and prevent the inward flow of contamination into the treatment zone from the surrounding area. It will also prevent the

outward migration of contaminants. In order to determine if migration is occurring, samples must be collected and analyzed in the treatment zone and the surrounding area before and after RFH. Changes in concentrations between samples inside the treatment zone would be compared to changes in concentrations between samples outside the treatment zone.

In evaluating the soil data to determine if contaminant migration had occurred, a number of problems with the SVE system were identified. A vapor barrier was installed to prevent air infiltration and consequent short-circuiting at the surface and to prevent the escape of fugitive emissions. The vapor barrier extended 10 feet laterally beyond the treatment zone boundaries on each of the four sides. With the particular operational configurations of vacuum wells selected, the presence of the vapor barrier resulted in low gas flows within much of the treatment area and in high flow rates from areas outside the treatment zone. This may have resulted in contaminant migration into the treatment zone from surrounding soils.

The original SVE system design called for three of the six surrounding wells (E6, E7, and E8) to be passive vent wells; air would be extracted from one or more of the other wells. This design would help to isolate the treatment zone, which would have minimized contaminant migration into it. However, during the demonstration, the SVE system was generally operated with no passive vent wells and a variety of different configurations of extraction wells. Wells not being used in any particular configuration were capped. Normally, two or more extraction wells were operated at the same time. With no passive vent wells, the soil gas flow rates would have been very low in the area bounded by the vacuum wells because the gas pressure gradients in this region would have been quite small. This would have been true even when the vacuum on the extraction wells was high. Since two or more extraction wells were generally in operation at one time, and there were no passive vent wells, and also since the area was covered by an impermeable cap, there would have been very little gas flow in most of the region lying within the polygon having the vacuum wells at its corners.

The extraction wells were generally screened well below the revised treatment zone, so that organics volatilized in the revised treatment zone may have condensed when drawn into the cooler underlying soil.

TRPH concentrations increased outside the revised treatment zone at the 80 percent confidence level. The estimated geometric mean increase was 39 percent. The increase is probably due to inward

vertical and lateral migration from the surrounding area. TRPH increased outside the original treatment zone at the 97.5 percent confidence level. The estimated geometric mean increase was 96 percent. This increase was probably due to the design and operation of the SVE system, which resulted in inward vertical and lateral migration from the surrounding area.

Because of the low concentrations of most target SVOCs in the pre- and post-treatment soil samples, only benzo(a)anthracene was present in sufficient quantity to make a statistical evaluation. It decreased 43 percent outside the revised treatment zone at the 90 percent confidence level; however, its decrease inside the original zone was not statistically significant. It is not known why this compound decreased outside the revised treatment zone.

High concentrations of several VOCs (toluene, chlorobenzene, methylene chloride) were detected in some soil samples, but the changes in concentrations were not statistically significant. However most target VOCs in the pre- and post-treatment soil samples had low concentrations, and a statistical evaluation could not be made.

Several groundwater samples were collected to characterize the site and to determine whether contaminants from the groundwater were migrating into the treatment zone. Chlorobenzene was one of the predominant contaminants in the groundwater, but very little chlorobenzene was detected in the revised and original treatment zones. The highest chlorobenzene concentrations were in the deeper soil, closer to the groundwater.

Pretreatment chlorobenzene concentrations in the soil within the revised treatment zone ranged from less than 22.7 ppb to less than 50 ppb, with none of the eight samples having concentrations above the PQL level. Because of the low pretreatment concentrations within the revised treatment zone, no statistically significant decrease could be observed. Chlorobenzene concentrations in the soil within the remainder of the original treatment zone were higher, but no statistically significant decrease was exhibited within the original treatment zone.

Chlorobenzene concentrations in the soil below the original treatment zone were significantly higher than those inside the revised and original treatment zones. Analyses of soil samples below 20 feet indicated chlorobenzene concentrations as high as 239,000 ppb in pretreatment and 291,000 ppb in post-treatment samples. Even with these high starting concentrations, no statistically significant decrease of

chlorobenzene was observed in the area outside the original treatment zone. However, this zone was not heated or screened during the demonstration and was not expected to show contaminant decrease.

In spite of the fact that no statistically significant chlorobenzene decrease was observed in the soil, SVE vapor stream data indicate significant amounts of chlorobenzene being extracted before, during, and after the heating stage of the demonstration. It is possible that the amount of chlorobenzene extracted from the soil was not enough to cause a statistically significant decrease. Alternatively, the chlorobenzene present in the SVE vapor stream may indicate some source of chlorobenzene other than the soil.

Significant concentrations of chlorobenzene were found in groundwater samples collected from surrounding wells before the demonstration. These wells are located outside of the treatment area sampled for this demonstration. Chlorobenzene concentrations are 12,000 ppb in MW-09, 25,500 ppb in MW-10, and 15,500 ppb in DW-02. This indicates that the groundwater, which is probably causing high levels of chlorobenzene outside the demonstration area, may be a source of the chlorobenzene in the SVE vapor stream.

4.5 **RESIDUALS**

The residuals resulting from the demonstration of the KAI RFH technology include soil; contaminant vapors removed from the soil; condensate collected within the vapor treatment system; washwater from equipment and personnel decontamination; and miscellaneous solid wastes, such as used PPE. All residuals remained the responsibility of Kelly AFB. The treated soil was left in place, and soil cuttings from drilling activities were drummed and removed from the site for disposal. Contaminant vapors that condensed within the vapor treatment system were collected and transferred to a Kelly AFB industrial wastewater treatment facility. Vapors that did not condense were channeled to a propane-fueled flare for destruction.

4.6 **REFERENCES**

1. American Society for Testing and Materials, Annual Book of ASTM Standards.
2. U.S. Environmental Protection Agency, Test Methods for Evaluating Solid Waste (SW-846): Third Edition, November, 1986, and Final Update, September, 1990.
3. U.S. Environmental Protection Agency, EPA Methods for Chemical Analysis of Water and Wastes, 1983.

SECTION 5

OTHER TECHNOLOGY REQUIREMENTS

5.1 ENVIRONMENTAL REGULATION REQUIREMENTS

State regulatory agencies may require permits for the onsite installation and operation of KAI's RFH system. An air emissions permit may be required for the vapor treatment system. If offsite disposal of contaminated residuals is required, the residuals must be removed from the site by a licensed transporter. These residuals must be treated or disposed of by a permitted incinerator or other treatment or disposal facility. Additional environmental regulations may apply, depending on the characteristics of the specific site and the contaminants present.

5.2 PERSONNEL ISSUES

Proper PPE should be available and properly utilized by all onsite personnel. PPE requirements will be site-specific and should be determined based on the contaminants present at the site and on the work activities being conducted. During the demonstration, PPE levels were designated according to the potential hazards associated with each work activity. At a minimum, Level D PPE was required for all personnel working at Site S-1. During most demonstration activities, site personnel were not in contact with the contaminated soil because it was covered with a layer of gravel. The potential for exposure to soil contaminants was increased during drilling activities, including pretreatment sampling, installation of subsurface system components, and post-treatment sampling.

Site monitoring should be conducted to identify the extent of hazards and to document exposures at the site. Monitoring results should be maintained and posted. During the demonstration, a flame ionization detector (FID) was used to monitor the air near the soil and in the breathing zone during drilling, groundwater sampling, and related activities. Because the degree of soil and groundwater contamination varied considerably, the drill crew and other personnel alternated use of Level C PPE and Level D PPE. They upgraded to Level C PPE when the FID indicated breathing zone air contaminant concentrations greater than 5 ppm over background for 5 minutes; they were permitted to downgrade to Level D when the FID indicated breathing zone air contaminant concentrations less than 5 ppm over background. Respirators were required periodically during both pre- and post-treatment sampling.

OSHA 40-hour training covering PPE application, safety and health, and emergency response procedures should be required for all personnel working with the RFH technology. Additional training provided prior to the operation of the system at a given site should include information regarding emergency evacuation procedures; safety equipment locations; the boundaries of the exclusion zone, contaminant reduction zone, and support zone; PPE requirements; and site- and technology-specific hazards. Potential hazards associated with the RFH technology include drilling accidents and personnel exposure to RF fields. Safe operating procedures should always be observed, particularly during drilling operations. Periodic monitoring for RF electromagnetic fields will also reduce the technology-specific hazards.

Onsite personnel should participate in a medical monitoring program. Health and safety monitoring and incident reports should be routinely filed, and records of occupational illnesses and injuries (OSHA Forms 102 and 200) should be maintained. Audits ensuring compliance with the health and safety plan should be carried out. In the event of an accident, illness, hazardous situation at the site, or intentional act of harm, assistance should be immediately sought from the local emergency response teams, and first aid or decontamination should be employed if appropriate. To ensure a timely response in case of an emergency, workers should review the evacuation plan, firefighting procedures, cardiopulmonary resuscitation (CPR) techniques, and emergency decontamination procedures before operating the system. An evacuation vehicle should be available at all times.

5.3 COMMUNITY ACCEPTANCE

Community acceptance of a technology is affected by both actual and perceived hazards. The fact that the RFH technology allows in situ remediation of contaminated soils should improve the potential for community acceptance, since excavation of contaminated soils often releases volatile contaminants. Although some contaminants are likely to be released during electrode and thermowell installation, the potential for emissions during drilling is substantially lower than during excavation.

Disadvantages associated with in situ RFH and other in situ technologies are the difficulty of determining whether the treatment zone has been uniformly remediated and the potential for contaminant migration if pockets of contamination remain in the soil. Actual or perceived hazards associated with the RF energy may also become an issue, as potential health effects of electromagnetic fields have recently received significant publicity. Some community education may be required to assure residents that the operation of the RFH system is in compliance with safety requirements and guidelines. The American

Conference of Governmental Industrial Hygienists (ACGIH) has established Threshold Limit Values (TLVs) for radio frequency radiation. The TLVs are dependent on the frequencies of the radio waves. TLVs and formulas for calculating TLVs are presented in Table 11. The RFH system used during the SITE demonstration was designed to operate at a frequency of 27.12 MHz. TLVs for this specific frequency are also presented in Table 11.

Table 11. Radio Frequency Radiation TLVs [1]

Frequency	Power Density (mW/cm^2)	Electric Field strength squared (V^2/m^2)	Magnetic Field strength squared (A^2/m^2)
27.12 MHz	1.22	4,613	0.033
30 kHz to 3 MHz	100	377,000	2.65
3 MHz to 30 MHz	$900/f^2$	$3,770 (900/f^2)$	$900/(37.7 \times f^2)$
30 MHz to 100 MHz	1	3,770	0.027
100 MHz to 1,000 MHz	$f/100$	$3,770 (f/100)$	$f/(37.7 \times 100)$
1 GHz to 300 GHz	10	37,700	0.265

f = frequency in MHz

REFERENCE

1. American Conference of Governmental Industrial Hygienists. Threshold Limit Value. 1992.

SECTION 6

TECHNOLOGY STATUS

KAI's RFH system was used to treat approximately 56 cubic yards of soil at Kelly AFB during the SITE demonstration. The soil in the treatment zone was contaminated with mixed solvents, carbon cleaning compounds, and petroleum oils and lubricants. The results of this demonstration are summarized briefly in Section 4 of this report and are summarized in greater detail in Appendix A.

Prior to the SITE demonstration conducted at Kelly AFB, KAI's RFH system was tested at several other sites. The results of two of these tests are available to the public. One test was conducted at the Savannah River Superfund site to investigate the effectiveness of the KAI RFH system as an enhancement to vacuum extraction. During the Savannah River test, KAI's RFH system was used in the removal of residual solvents (primarily trichloroethylene and perchloroethylene) from vadose zone clay deposits approximately 40 feet bgs. A second test was conducted to evaluate the ability of the KAI RFH system to enhance the removal of #2 Fuel Oil from silty soil. Both tests are described in greater detail in Appendix B.

APPENDIX A

Performance Data

A.1 CHEMICAL ANALYSES

A.1.1 Procedure for Selecting Contaminants for Statistical Evaluation

All **soil** samples were analyzed for TRPH, and half of the soil samples were analyzed for VOCs and SVOCs. TRPH in the soil samples was extracted by Method 9071A prior to analysis by Method 418.1. VOCs in the soil samples were analyzed by Method 8240. Target VOCs are listed in Section 4, Table 5. SVOCs in the soil samples were extracted by Method 3540 prior to analysis by Method 8270. Target SVOCs are listed in Section 4, Tables 6 and 7.

The first step of the data evaluation process was to count the number of pretreatment samples in which each target compound was detected above its method detection limit (MDL). Many target VOCs and SVOCs were not detected in any pretreatment samples. Table A-1 lists those compounds that were detected and the number of samples in which each compound was detected above its MDL.

Only 13 contaminants were detected above their MDLs in over 15 samples (numbers shown in bold in the second column of Table A-1). The number of complete matched data pairs inside the original treatment zone was determined for each of these 13 contaminants. A complete matched pair consists of a pretreatment sample and a post-treatment sample collected as close as possible to the pretreatment sample. In order to be included in the evaluation process for a given compound, a matched pair must also meet the following criteria:

- 1) The pre- and post-treatment concentrations of the selected compound must not both be below their MDLs.
- 2) If either the pretreatment or post-treatment concentration of the selected compound is below its MDL, its MDL must not be greater than the measured concentration of the other sample.

As shown in Table A-1, six of the contaminants evaluated had 10 or more complete matched pairs within the original treatment zone (numbers shown in bold in the third column of Table A-1). Practical quantitation limits (PQLs) of five times the MDLs were calculated for all data points for each

Table A-I. Summary of Data Evaluation Process

Contaminant	# of pretreatment samples in which contaminant was detected above its MDL	# of complete matched pairs within the original treatment zone, based on MDLs	# of complete matched pairs within the revised treatment zone, based on PQLs
TRPH	64	40	20
Acetone	14		
Benzene	2		
Chlorobenzene	29	9	2
Ethylbenzene	5		
Methyl ethyl ketone	22^a		
Methylene chloride	20	0	0
Tetrachloroethene	1		
Toluene	20	3	1
Trichloroethene	1		
Xylenes	11		
Acenaphthene	7		
Anthracene	9		
Benzo(a)anthracene	16	13	5
Benzo(a)pyrene	15	13	4
Benzo(b)fluoranthene	17	14	5
Bis(2-ethylhexyl)phthalate	27	16	5
2-Chlorophenol	1		
Chrysene	16	12	5
Dibenz(ah)anthracene	4		
Dibenzofuran	5		
1,2-Dichlorobenzene	14		
1,3-Dichlorobenzene	14		
1,4-Dichlorobenzene	15		
2,4-Dimethylphenol	5		
Di-n-butylphthalate	10		
Fluoranthene	27	19	
Fluorene	13		
Hexachlorobenzene	2		
Indeno (123cd)pyrene	11		
2-methylnaphthalene	20	9	
Naphthalene	15		
Phenanthrene	23	13	0
1,2,4-Trichlorobenzene	6		
Pyrene	22	18	5
TOTALS	519	188	57

a Similar concentrations were observed in laboratory blanks; therefore, this compound was not considered during the statistical analyses.

of these six contaminants; these PQLs were then used during the statistical analyses. The use of PQLs eliminates estimated values and results in more conservative evaluations. The number of complete matched data pairs inside the original treatment zone was then redetermined for these six contaminants, based on PQLs rather than MDLs.

Because the PQLs were five times the MDLs, the conversion to PQLs eliminated many complete matched pairs. In addition, the SITE Program was informed at this point that KAI and B&RE changed the test plan during installation and decided to heat only the upper half (approximately) of the original treatment zone. Throughout this document, the upper half of the original treatment zone is referred to as the “revised treatment zone”, which ranges in depth from 4 feet to 14 feet. When the evaluation was changed to the revised treatment zone, this further reduced the number of complete matched pairs. As shown in the last column of Table A-1, TRPH had 20 complete matched pairs, within the heated zone (using PQLs). All other contaminants evaluated had between zero and seven complete matched pairs within the revised treatment zone.

As a result, paired t-tests for the revised treatment zone were performed on all VOCs which met the first requirement. Paired t-tests were performed on all SVOCs which met the first two requirements and also contained three or greater matched pairs in the revised zone. Results are reported only for those compounds that exhibited statistically significant changes at confidence levels of 80 percent or greater. The methodology for conducting a paired t test for a given compound is described in the following subsection

A.1.2 Methodology for Statistical Evaluation

The number of complete matched pairs for a given contaminant was determined and was represented by N. Because the TRPH data were found to be log-normally distributed, logarithms of all data were calculated before the data were manipulated. X_0 was used to represent the pretreatment log concentration of this compound from the i^{th} sample location, and X_{i1} was used to represent the post-treatment log concentration from the i^{th} sample location (where i varied from 1 to N). The difference in log concentrations ($X_{i1} - X_0$) was calculated for each data pair and was denoted by d_i . The mean of the differences in log concentrations was calculated according to the following formula:

$$\bar{d} = \frac{1}{N} \sum_{i=1}^N d_i$$

R was used to represent the geometric mean of the ratios of post-treatment concentration to pretreatment concentration, which was calculated from the geometric mean of the differences in log concentrations according to the following formula:

$$R = 10^{\bar{d}}$$

R was then converted to either percent decrease or percent increase, as appropriate.

The standard deviation of the differences in log concentrations was calculated according to the following formula:

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (d_i - \bar{d})^2}$$

It was assumed that the unknown pre- and post-treatment logmean concentrations throughout the entire site were μ_0 and μ_1 , respectively, and the logvariances were equal. The following equation defines the statistic used in the paired t-test:

$$t = \frac{\bar{d}}{s} \sqrt{N}$$

The resulting value of t was compared to tabulated values of t for two-tailed tests to determine the probability that the measured change (percent decrease or percent increase) was representative of the revised treatment zone.

A.1.3 Data Summary

TRPH

Tables A-2 through A-7 present pre- and post-treatment TRPH data from analyses of soil samples. The sample locations presented in these tables correspond to the subsurface components labeled on Figure 1.

Table A-2. TRPH Samples Revised Zone (ppm)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment - Pretreatment Value
E1-U1012	3,350	1,160	-2,190
E6-U0810	1,860	930	-930
F1-U0406	6,910	828	6,082
F1-U1012	1,240	1,580	340
E4-U0709	1,310	1,090	-220
E4-U0911	729	593	-136
F4-U1214	1,790	643	-1,147
E2-U1012	168.5*	582	414
F3-U0406	4,920	702	-4,218
F3-U1012	336	4,510	4,174
E7-U1214	1,400	825	-575
E5-U0406	2,710	673	-2,037
E5-U0608	1,530	587	-943
E5-U1012	668	330	-338
E5-U1214	739	1,450	711
F5-U1214	1,220	1,530	310
A2-U0406	1,530	154	-1,376
A2-U1012	1,290	33.3 *	-1,257
A2-U1214	622	106	-516
E8-U0608	655	861	206

Table A-3. TRPH Samples Original Treatment Zone (ppm)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment - Pretreatment Value
E1-U0002	352	4,830	-4,478
E1-U1012	3,350	1,160	2,190
E1-U1618	22,000	19,200	2,800
A1-U0002	458	184	274
A1-U1618	79,700	20,800	58,900
A1-U1820	39,300	28,300	11,000
E6-U0810	1,860	930	930
E6-U1618	3,160	253	2,907
F1-U0406	6,910	828	6,082
F1-U1012	1,240	1,580	-340
F1-U1820	5,440	23,100	-17,660
E4-U0709	1,310	1,090	220
E4-U0911	729	593	136
F4-U0002	1,220	448	772
F4-U1214	1,790	643	1,147
F4-U1618	1,090	12,500	-11,410
E2-U0002	1,730	3,620	-1,890
E2-U1012	168.5*	582	-414
F3-U0406	4,920	702	4,218
F3-U1012	336	4,510	-4,174
E7-U0204	492	161	331
E7-U1214	1,400	825	575
F2-U1416	3,250	555	2,695
E5-U0406	2,710	673	2,037
E5-U0608	1,530	587	943
E5-U1012	668	330	338
E5-U1214	739	1,450	-711
E5-U1820	105,000	35,800	69,200
F5-U1214	1,220	1,530	-310

Table A-3. (continued)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment - Pretreatment Value
F5-U1618	22,100	20,900	1,200
F5-U1820	35,000	53,200	-18,200
E3-U1416	1,210	1,770	-560
E3-U1618	7,410	2,820	4,590
A2-U0002	2,330	8,850	-6,520
A2-U0204	203	2,570	-2,367
A2-U0406	1,530	154	1,376
A2-U1012	1,290	33.3*	1,257
A2-U1214	622	106	516
A2-U1618	23,800	6,500	17,300
E8-U0608	655	861	-206

Table A-4. TRPH Samples Outside Revised Treatment Zone (ppm)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment- Pretreatment Value
E1-U0002	352	4,830	4,478
E1-U1618	22,000	19,200	-2,800
E1-U2425	4,690	6,830	2,140
A1-U0002	458	184	-274
A1-U1618	79,700	20,800	-58,900
A1-U1820	39,300	28,300	-11,000
A1-U2728	2,240	5,880	3,640
E6-U1618	3,160	253	-2,907
E6-U2022	22,700	92,600	69,900
F1-U1820	5,440	23,100	17,660
E4-U2426	3,660	3,170	-490
F4-U0002	1,220	448	-772
F4-U1618	1,090	12,500	11,410
F4-U2829 ¹	1,670*	1,520	-150
E2-U0002	1,730	3,620	1,890
E2-U2628	4,440	23,100	18,660
F2-U1416	3,250	555	-2,695
F2-U2628	4,440	6,270	1,830
E5-U1820	105,000	35,800	-69,200
E5-U2022	43,500	31,200	-12,300
F5-U1618	22,100	20,900	-1,200
F5-U1820	35,000	53,200	18,200
F5-U2324	10,300	7,590	-2,710
E3-U1416	1,210	1,770	560
E3-U1618	7,410	2,820	-4,590
E3-U2022	1,360	58,800	57,440
E3-U2829	325	3,810	3,485
A2-U0002	2,330	8,850	6,520
A2-U1618	23,800	6,500	-17,300

Table A-4. (continued)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment- Pretreatment Value
A2-U2022	21,200	58,900	37,700
A2-U2628	2,730	4,800	2,070
E8-U2426	10,100	6,060	4,040
E8-U2628	2,060	3,060	1,000
TD3-U0406	1,420	4,740	3,320
TD3-U1416	171.5*	1,940	1,769
TD3-U2426	5,700	5,040	660
TD5-U0406	445	762	317
TD5-U1416	31,300	1,540	-29,760
TD5-U2425	2,080	14,300	12,220
TD6-U0406	538	893	355
TD6-U1416	2,980	6,120	3,140
TD6-U2527	2,940	2,020	-920

- 1 Because the pretreatment PQL for this sample pair is greater than the post-treatment concentration, this sample pair was not included in the statistical evaluation of the data.

Table A-5. TRPH Samples Outside Original Treatment Zone (ppm)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment- Pretreatment Value
E1-U2425	4,690	6,830	2,140
A1-U2728	2,240	5,880	3,640
E6-U2022	22,700	92,600	69,900
E4-U2426	3,660	3,170	-490
F4-U2829¹	1,670*	1,520	-150
E2-U2628	4,440	23,100	18,660
F2-U2628	4,440	6,270	1,830
E5-U2022	43,500	31,200	-12,300
F5-U2324	10,300	7,590	-2,710
E3-U2022	1,360	58,800	57,440
E3-U2829	325	3,810	3,485
A2-U2022	21,200	58,900	37,700
A2-U2628	2,730	4,800	2,070
ES-U2426	10,100	6,060	-4,040
ES-U2628	2,060	3,060	1,000
TD3-U0406	1,420	4,740	3,320
TD3-U1416	171.5*	1,940	1,769
TD3-U2426	5,700	5,040	-660
TD5-U0406	445	762	317
TD5-U1416	31,300	1,540	-29,760
TD5-U2425	2,080	14,300	12,220
TD6-U0406	538	893	355
TD6-U1416	2,980	6,120	3,140
TD6-U2527	2,940	2,020	-920

¹ Because the pretreatment PQL for this sample pair is greater than the post-treatment concentration, this sample pair was not included in the statistical evaluation of the data.

Table A-6. TRPH Samples AI Zone (ppm)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment - Pretreatment Value
EI-U1012	3,350	1,160	-2,190
E6-U0810	1,860	930	-930
FI-U0406	6,910	828	-6,082
FI-U1012	1,240	1,580	340
E4-U0709	1,310	1,090	-220
E4-U0911	729	593	-136
F4-U1214	1,790	643	-1,147
E2-U1012	168.5*	582	414
F3-U0406	4,920	702	4,218
F3-U1012	336	4,510	4,174
E7-U1214	1,400	825	-575
E5-U0406	2,710	673	-2,037
E5-U0608	1,530	587	-943
E5-U1012	668	330	-338
E5-U1214	739	1,450	711

Table A-7. TRPH Samples A2 Zone (ppm)

Sample Location	Pretreatment Reported Value (* if PQL)	Post-treatment Reported Value (* if PQL)	Post-treatment - Pretreatment Value
E2-U1012	168.5*	582	414
E4-U0709	1,310	1,090	-220
E4-U09 11	729	593	-136
F3-U0406	4,920	702	-4,218
F3-U1012	336	4,510	4,174
E7-U1214	1,400	825	-575
E5-U0406	2,710	673	-2,037
E5-U0608	1,530	587	-943
E5-U1012	668	330	-338
E5-U1214	739	1,450	711
F5-U1214	1,220	1,530	310
A2-U0406	1,530	154	-1,376
A2-U1012	1,290	33.3*	-1,257
A2-U1214	622	106	-516
E8-U0608	655	861	206

Table A-8 summarizes the TRPH pretreatment and post-treatment concentration geometric means and percent decreases. Figure A-1 summarizes the TRPH contaminant concentrations used in the final statistical evaluation. To illustrate sampling locations, the results are presented on cross-sections of the original design treatment zone. This figure consists of three cross-sections of the original design treatment zone. The first cross-section shows samples collected from the ground electrode row E-1 to E-3, the second cross-section shows samples collected from the exciter electrode row, and the third cross-section shows samples collected from ground electrode row E6 through E8. TD3 is actually outside the original treatment zone entirely, but is included in the first cross-section for convenience. TD5 and TD6 are included in the second cross-section because they are in line with the exciter electrodes.

Both the original and revised design treatment zones are shown on the cross-sections. For each cross-section, samples included in the original treatment zone are inside a box formed by a thin black line. Samples included in the revised treatment zone are inside a box formed by a thick black line.

In Figure A-1, the TRPH concentration is presented on a dry-weight basis. When TRPH was not detected at or above its PQL, the PQL is presented. An asterisk to the right of a value indicates that value is the PQL, rather than a measured concentration.

SVOCs and VOCs

Tables A-9 and A-10 summarize the pre- and post-treatment geometric mean concentrations and percent decreases in each of the zones for the primary SVOC and VOC contaminants respectively. Figures A-2 through A-9 summarize the SVOC and VOC contaminant concentrations used in the final statistical evaluation. These figures are in the same format as the data presented for TRPH in Figure A-1.

SVE Vapor Stream

The vapor stream was sampled and analyzed at six critical points during the demonstration. Sampling times are summarized in Table A-11, and vapor extraction system conditions during sampling are summarized in Table A-12. Concentrations of VOCs and SVOCs in the vapor stream from the six sampling points are summarized in Tables A-13 and A-14, respectively.

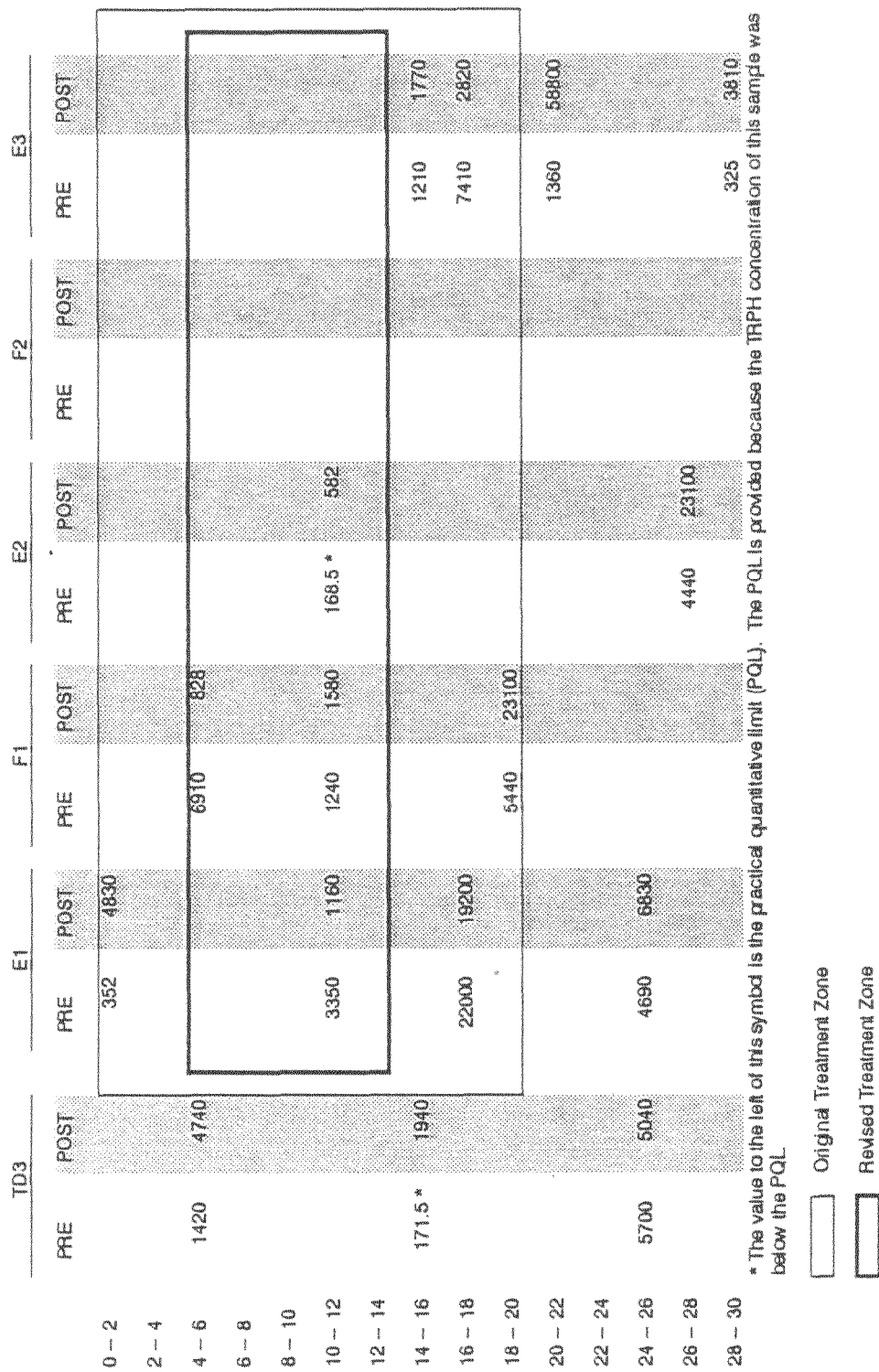


Figure A-1. KAI TRPH concentrations (ppm).

	A1		E4		F3		E5		A2		TD6		TD5	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2	458	184							2330	8850				
2 - 4									203	2570				
4 - 6					4920	702	2710	679	1530	154	538	893	445	762
6 - 8			1310	1090			1530	587						
8 - 10			729	593										
10 - 12					336	4510	668	330	1290	33.3 *				
12 - 14							739	1450	622	106				
14 - 16											2980	6120	31300	1540
16 - 18	79700	20800							23800	6500				
18 - 20	39300	28300					105000	35800						
20 - 22							43500	31200	21200	58900				
22 - 24														
24 - 26			3660	3170									2080	14300
26 - 28	2240	5880												
28 - 30									2730	4900	2940	2020		

* The value to the left of this symbol is the practical quantitative limit (PQL). The PQL is provided because the TPH concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-1. (continued)

	E6		F4		E7		F5		E8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			1220	448						
2 - 4					492	161				
4 - 6										
6 - 8									655	661
8 - 10	1860	930								
10 - 12										
12 - 14			1790	643	1400	825	1220	1530		
14 - 16										
16 - 18	3160	253	1090	12500	3250	555	22100	20900		
18 - 20							35000	53200		
20 - 22	22700	92600								
22 - 24							10300	7590		
24 - 26									10100	6060
26 - 28					4440	6270			2060	3060
28 - 30			1670 *	1520						

* The value to the left of this symbol is the practical quantitative limit (PQL). The PQL is provided because the TRPH concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-1. (continued)

Table A-8. Summary of TRPH Percent Change

Treatment Zone	Pretreatment Geometric Mean (ppm)	Post-treatment Geometric Mean (ppm)	Percent Change
Revised	1,238	636.9	49% decrease^b
original	2,141	1,497	29% decrease^a
Outside Revised	4,259	5,862	39 % increase^c
Outside Original	3,289	6,444	96% increase^d
A1	1,382	1,008	—^a
A2	981	520	44% decrease^e

a Not accepted at an 80 percent significance level.

b Accepted at a 95 percent **significance** level.

c Accepted at an 80 percent significance level.

d Accepted at a 97.5 percent significance level.

e Accepted at a 90 percent significance level.

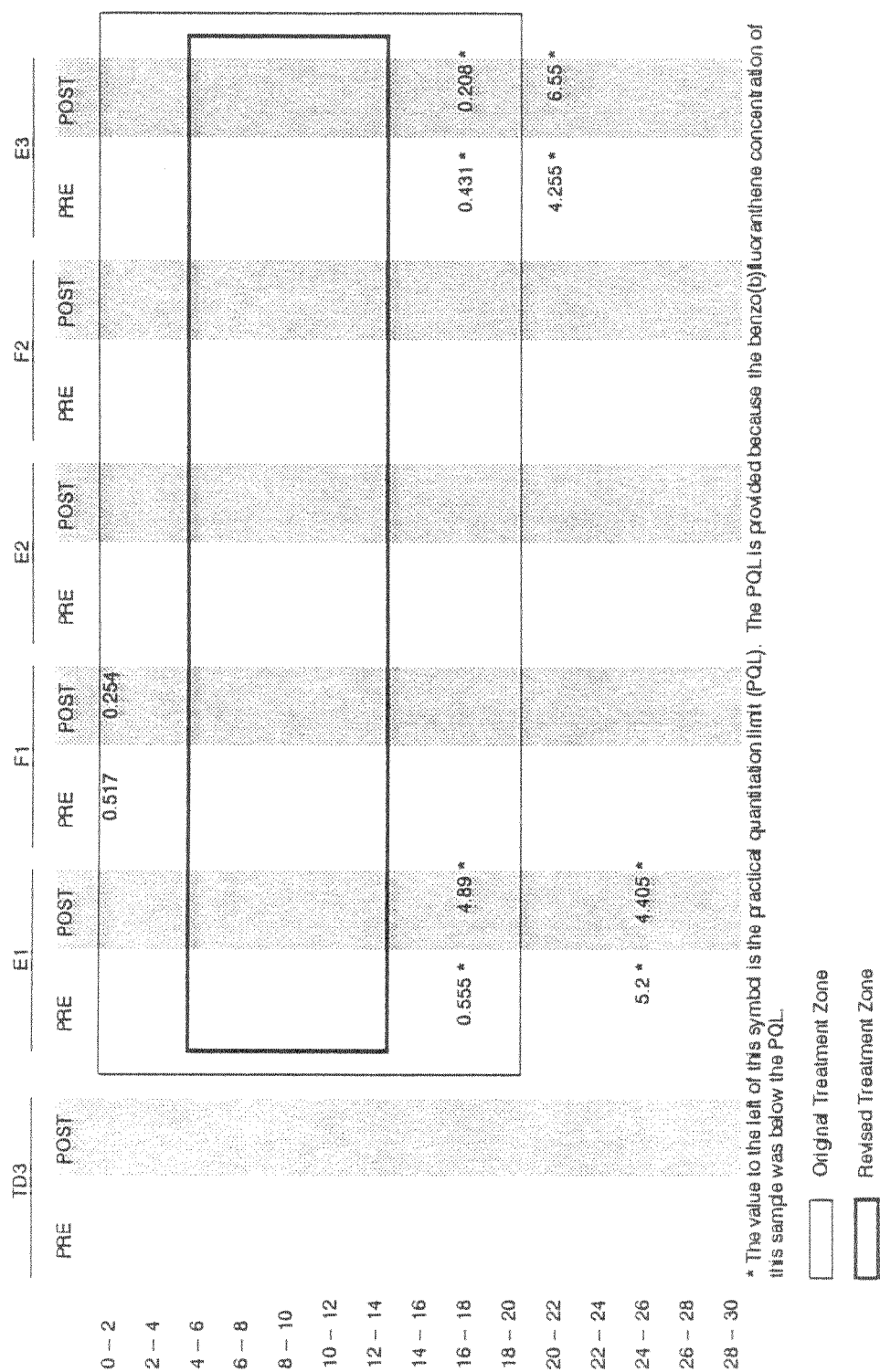


Figure A-2 Benzo(b)fluoranthene concentration (ppm).

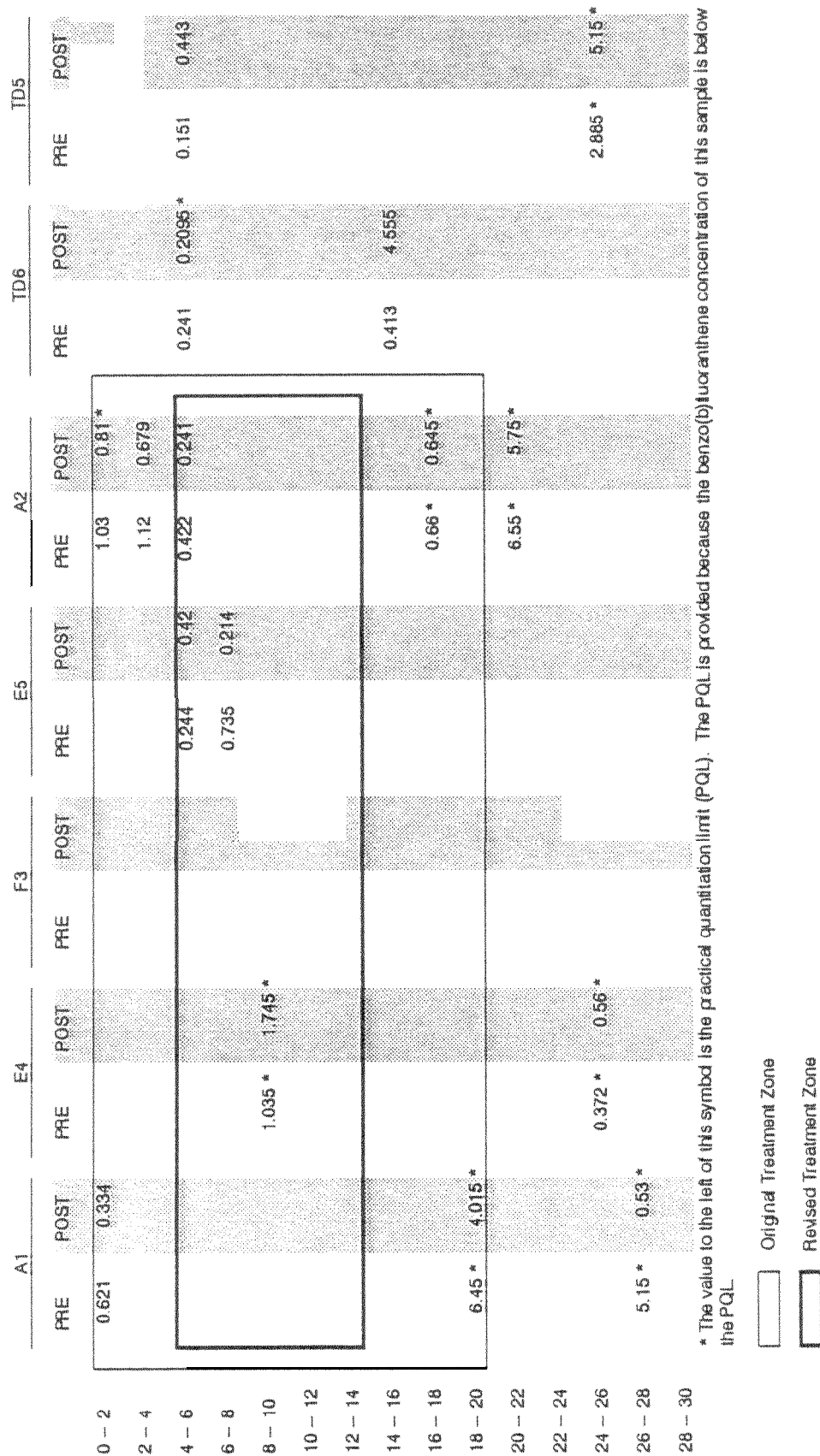


Figure A-2. (continued)

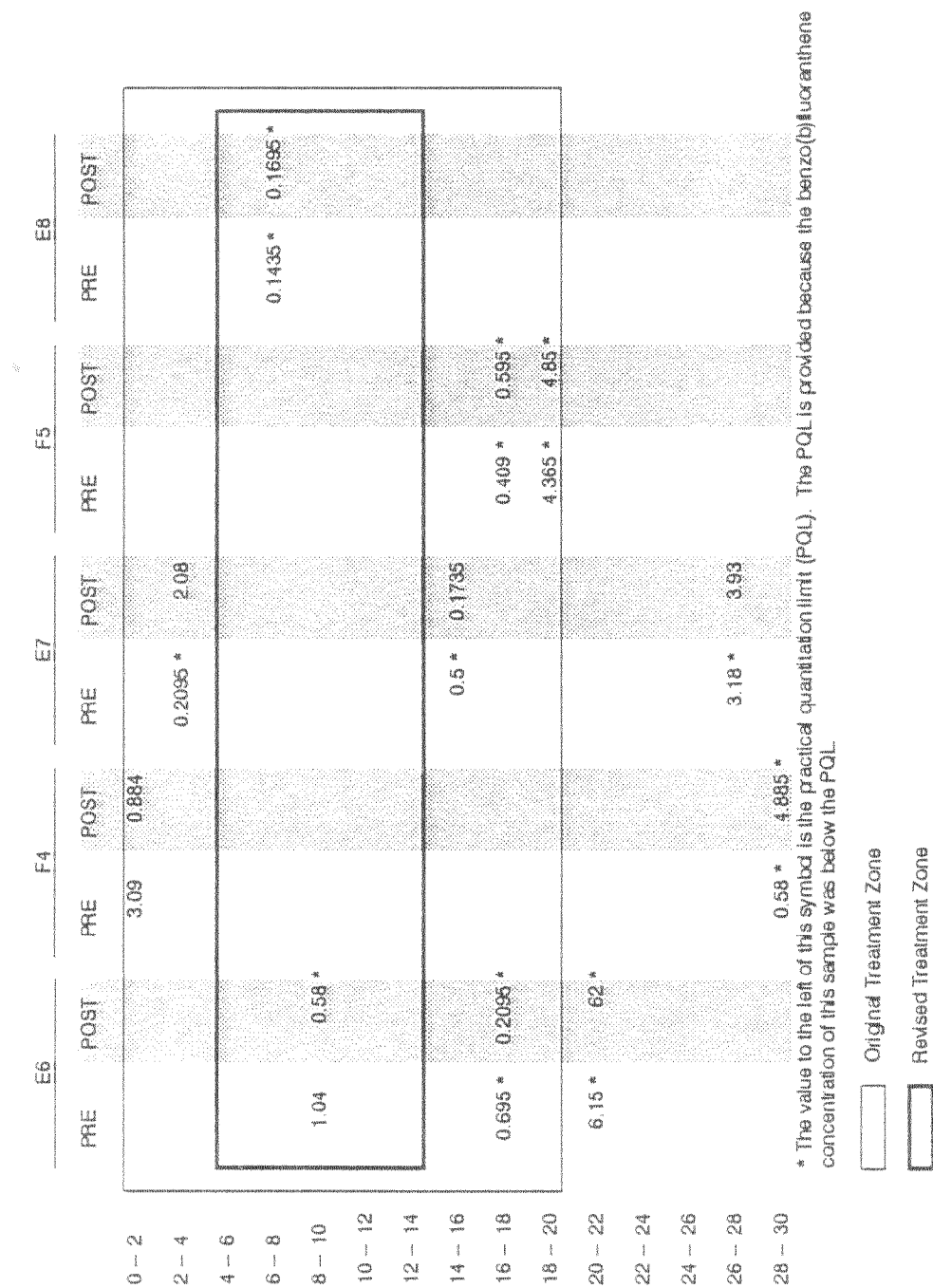


Figure A-2. (continued)

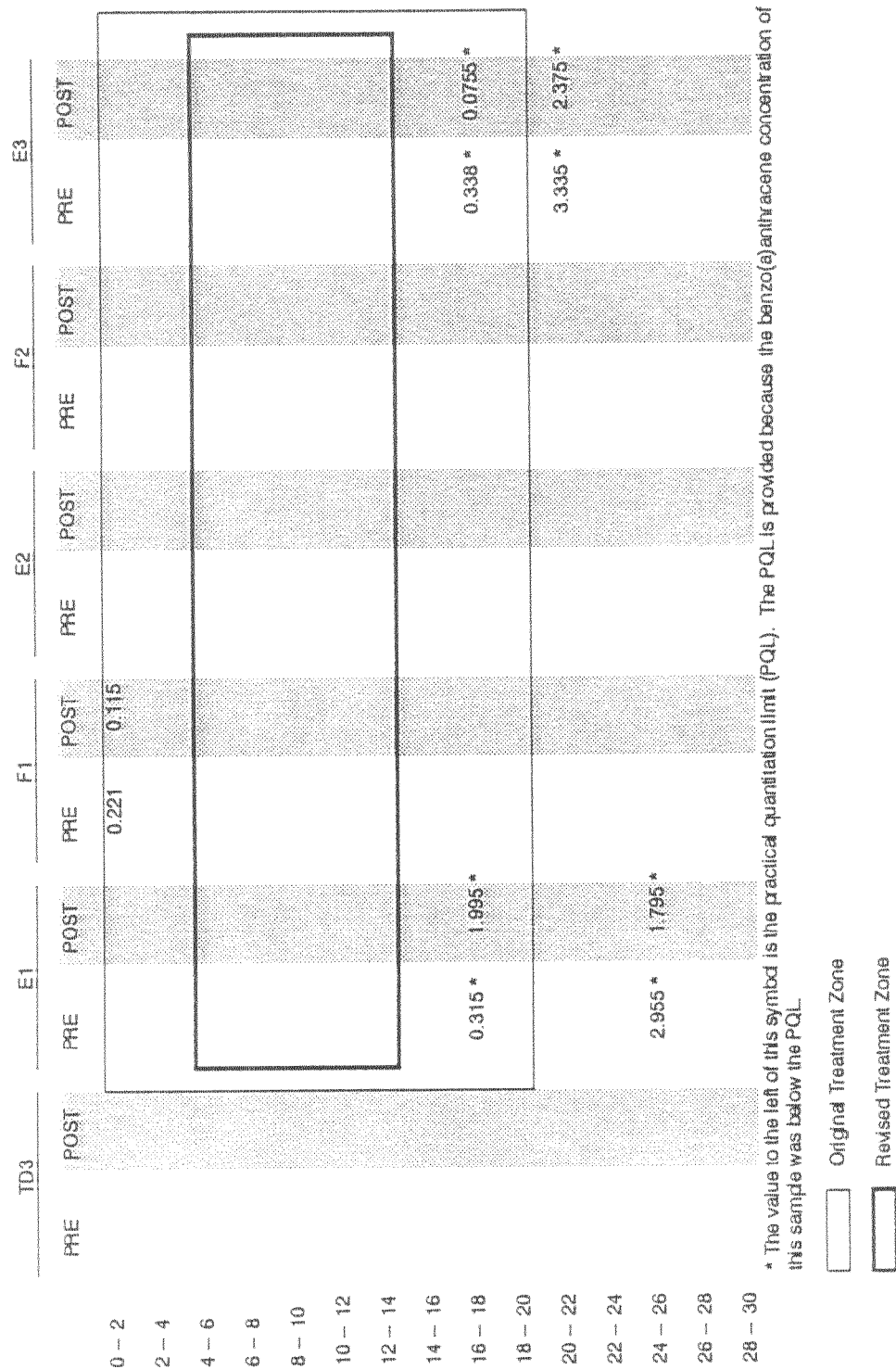


Figure A-3. Benzo(a)anthracene concentration (ppm).

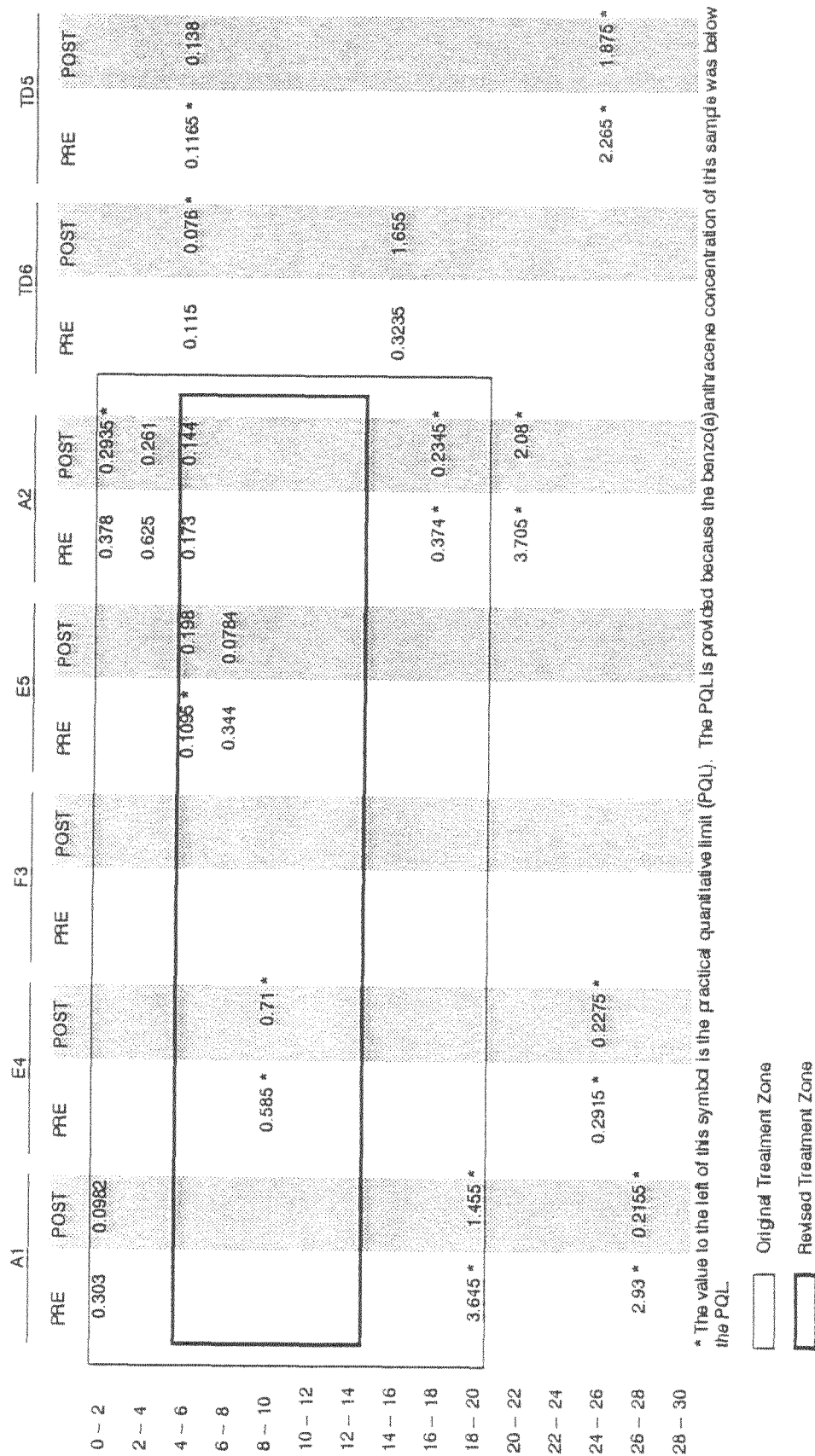


Figure A-3. (continued)

	E6		F4		E7		F5		E8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			1.09	0.329						
2 - 4					0.1185 *	1.82				
4 - 6										
6 - 8									0.1125 *	0.0615 *
8 - 10	0.4	0.21 *								
10 - 12										
12 - 14										
14 - 16					0.3935 *	0.063				
16 - 18	0.393 *	0.076 *					0.3205 *	0.2165 *		
18 - 20							3.42 *	1.98 *		
20 - 22	3.49 *	22.6 *								
22 - 24										
24 - 26										
26 - 28					2.495 *	1.605				
28 - 30					0.328 *	1.995 *				

* The value to the left of this symbol is the practical quantitative limit (PQL). The PQL is provided because the benzo(a)anthracene concentration of this sample was below the PQL

Original Treatment Zone

Revised Treatment Zone

Figure A-3 (continued)

	TD3		E1		F1		E2		F2		E3	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2					0.24	0.441 *						
2 - 4												
4 - 6												
6 - 8												
8 - 10												
10 - 12												
12 - 14												
14 - 16												
16 - 18			0.0842 *	0.622 *							0.0854 *	0.469 *
18 - 20												
20 - 22												
22 - 24											0.834 *	0.737 *
24 - 26												
26 - 28			0.79 *	0.56 *								
28 - 30												

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the benzo(a)pyrene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-4. Benzo(a)pyrene concentrations (ppm).

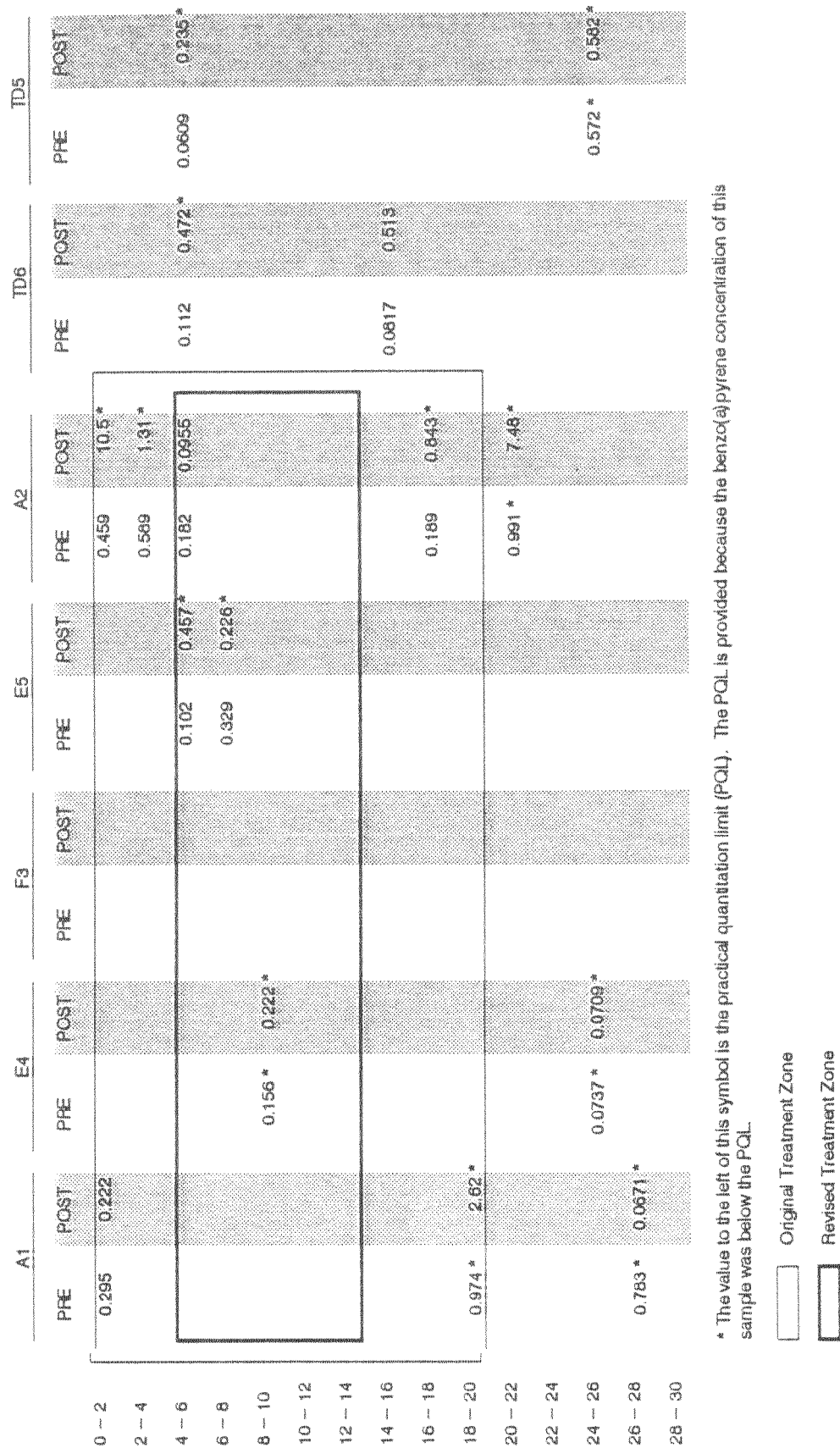


Figure A-4. (continued)

	E6		F4		E7		F5		E8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			1.53	0.496 *						
2 - 4					0.0831	1.15				
4 - 6										
6 - 8										
8 - 10	0.436	1.3 *							0.0385	0.381 *
10 - 12										
12 - 14										
14 - 16					0.0994 *	0.226				
16 - 18	0.105	0.236 *					0.0825	0.776 *		
18 - 20							0.864 *	0.617 *		
20 - 22	0.933 *	7.01 *								
22 - 24										
24 - 26										
26 - 28					0.63 *	0.5				
28 - 30			0.0876	0.621 *						

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the benzo(a) pyrene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-4. (continued)

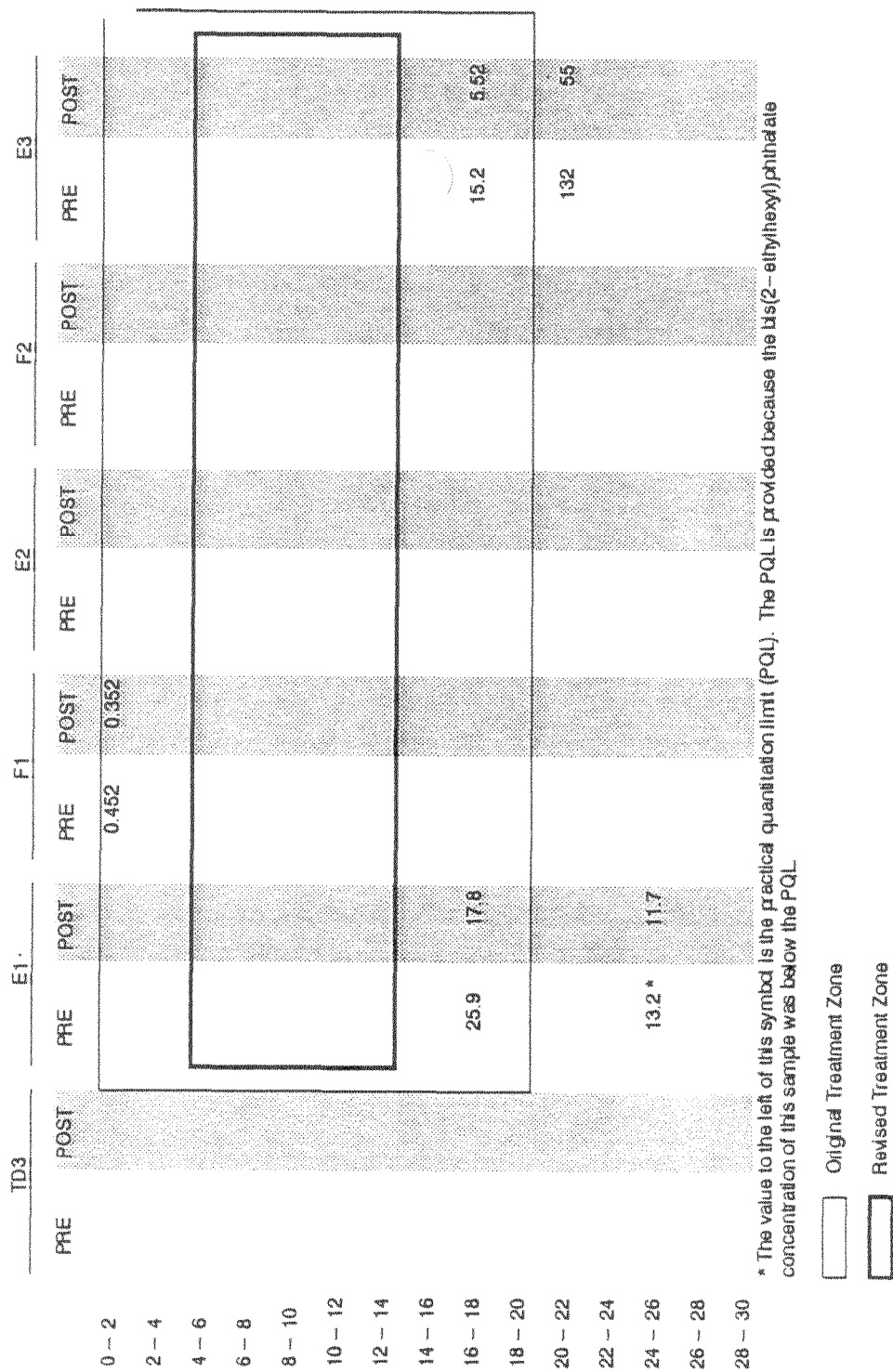


Figure A-5. Bis(2-ethylhexyl)phthalate concentrations (ppm).

	A1		E4		F3		E5		A2		TD6		TD5	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2	0.545 *	0.2615 *							1.32	1.38 *				
2 - 4									0.56 *	1.65				
4 - 6							0.908	1.31	0.686	0.2945 *	0.309	0.563	6.69	0.3575 *
6 - 8							0.725	0.296 *						
8 - 10			2.61 *	3.14 *										
10 - 12														
12 - 14														
14 - 16											1.55	35.6		
16 - 18									27.1	8.5				
18 - 20	73	30.9												
20 - 22														
22 - 24									16.55 *	14.1				
24 - 26			2.73	3.34									6.1 *	13.7
26 - 28	13.1 *	4.61												
28 - 30														

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the bis(2-ethylhexyl)phthalate concentration of this sample was below the PQL

Original Treatment Zone
Revised Treatment Zone

Figure A-5. (continued)

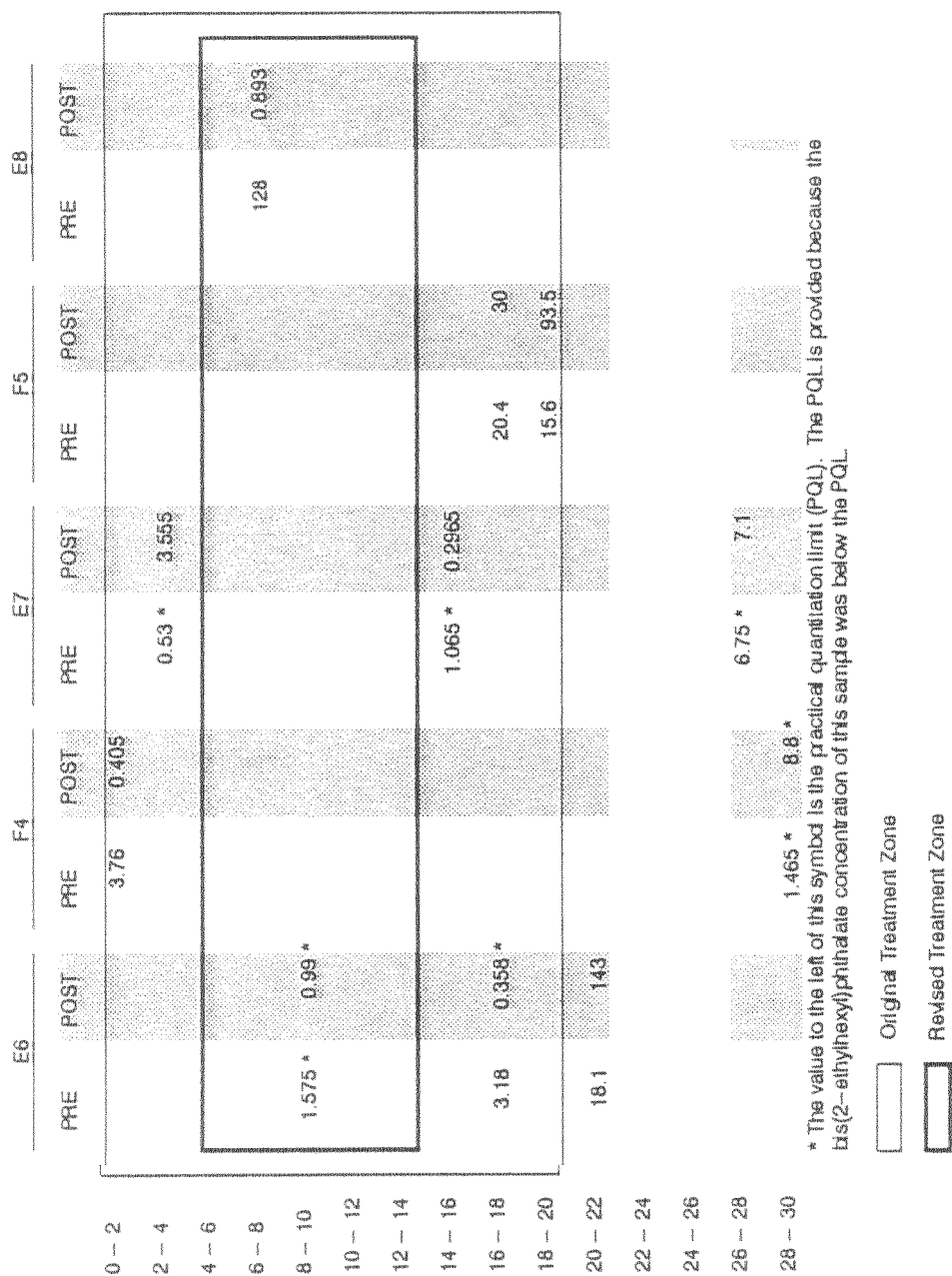


Figure A-5. (continued)

	ID3		E1		F1		E2		F2		E3	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2					0.382	0.161						
2 - 4												
4 - 6												
6 - 8												
8 - 10												
10 - 12												
12 - 14												
14 - 16												
16 - 18			0.525 *	1.365 *							0.447 *	0.127 *
18 - 20												
20 - 22											4.41 *	3.995 *
22 - 24												
24 - 26			4.925 *	1.23 *								
26 - 28												
28 - 30												

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the chrysene concentration of this sample was below the PQL

Original Treatment Zone

Revised Treatment Zone

Figure A-6. Chrysene Concentrations (ppm)

	A1		E4		F3		E5		A2		TD6		TD5	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2	0.355	0.244							0.438	0.493 *				
2 - 4									0.59	0.3105 *				
4 - 6							0.145 *	0.227	0.215	0.172				
6 - 8							0.388	0.1055 *			0.1425 *	0.128 *	0.1545 *	0.24
8 - 10			0.975 *	0.486 *										
10 - 12														
12 - 14														
14 - 16											0.428			
16 - 18									0.625 *	0.3945 *				
18 - 20	6.05 *	2.45 *											2.995 *	3.155 *
20 - 22									6.2 *	3.5 *				
22 - 24														
24 - 26			0.386 *	0.1555 *										
26 - 28	4.88 *	0.147 *												
28 - 30														

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the chrysene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-6. (continued)

	E6		F4		E7		F5		E8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			1.23	0.446						
2 - 4					0.198 *	1.63				
4 - 6										
6 - 8									0.1485 *	0.1035 *
8 - 10	0.65	0.3535 *								
10 - 12										
12 - 14										
14 - 16					0.52 *	0.106				
16 - 18	0.655 *	0.1275 *					0.424 *	0.364 *		
18 - 20							4.525 *	1.35 *		
20 - 22	5.8 *	37.95 *								
22 - 24										
24 - 26										
26 - 28					3.3 *	1.095				
28 - 30			0.545 *	1.36 *						

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the chrysene concentration of this sample was below the PQL

Original Treatment Zone
Revised Treatment Zone

Figure A-6. (continued)

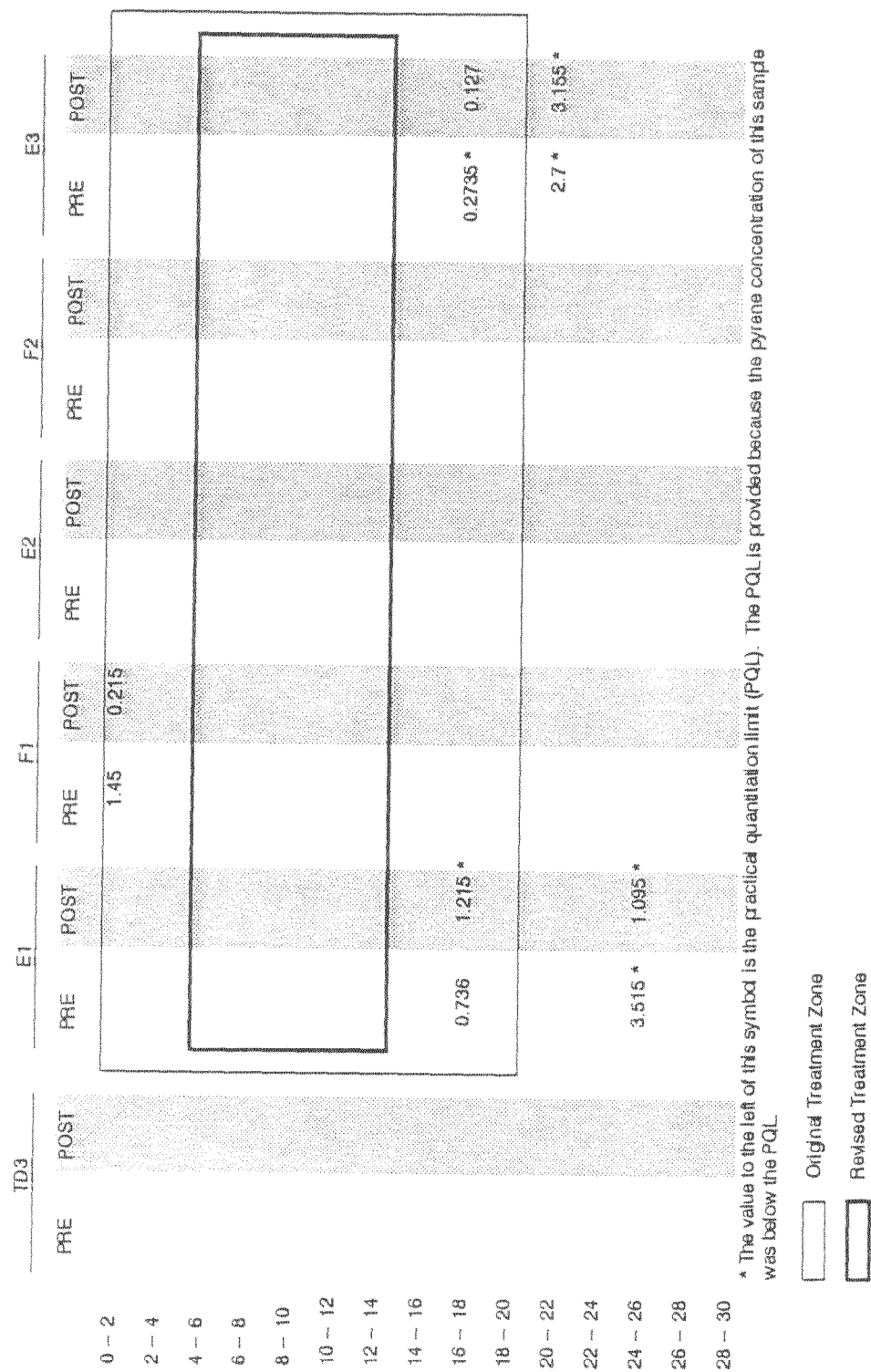


Figure A-7. Pyrene Concentrations (ppm).

	A1		E4		F3		E5		A2		TD6		TD5	
	PRI	POST	PRI	POST	PRI	POST	PRI	POST	PRI	POST	PRI	POST	PRI	POST
0 - 2	0.564	0.0795 *							0.652	0.3895 *				
2 - 4									0.911	0.409				
4 - 6							0.194	0.37	0.321	0.13				
6 - 8							0.591	0.18						
8 - 10			0.695 *	0.433 *							0.16	0.101 *	0.0945 *	0.22
10 - 12														
12 - 14														
14 - 16											0.262	2.195		
16 - 18									0.445 *	0.3115 *				
18 - 20	4.335 *	1.935 *												
20 - 22									4.41 *	2.765 *				
22 - 24														
24 - 26			0.236 *	0.1385 *									1.83 *	2.49 *
26 - 28	3.485 *	0.148												
28 - 30														

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the pyrene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-7. (continued)

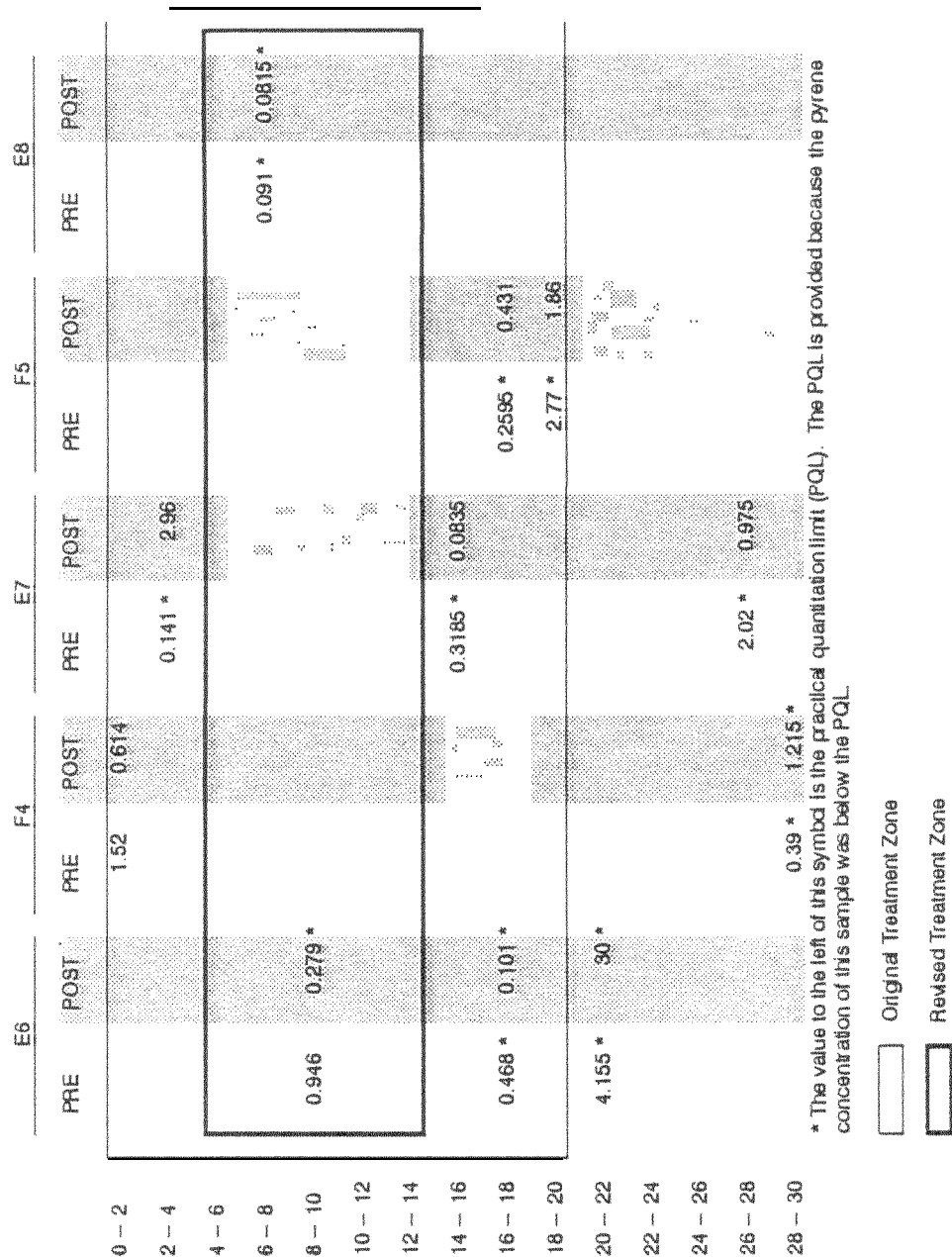


Figure A-7. (continued)

	TD3		E1		F1		E2		F2		E3	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2					0.55	0.249						
2 - 4												
4 - 6												
6 - 8												
8 - 10												
10 - 12												
12 - 14												
14 - 16												
16 - 18			3.1	0.84 *							0.3845 *	0.149
18 - 20												
20 - 22											26.2	15.1
22 - 24												
24 - 26			2.93 *	1.03								
26 - 28												
28 - 30												

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the fluoranthene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-8. Fluoranthene Concentrations (ppm).

	A1		E4		F3		E5		A2		TD6		TD5	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2	0.679	0.119							0.821	0.358 *				
2 - 4									1.16	0.57				
4 - 6							0.203	0.29	0.339	0.341	0.218	0.093 *	0.1325 *	0.196
6 - 8							0.872	0.126						
8 - 10			0.58 *	0.3 *										
10 - 12														
12 - 14														
14 - 16											0.368	2.02		
16 - 18									0.562	0.2865 *				
18 - 20	5.18	4.19												
20 - 22									3.675 *	6.52			2.575 *	2.88
22 - 24														
24 - 26			0.703	0.543										
26 - 28	2.905 *	0.852												
28 - 30														

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the fluoranthene concentration of this sample was below the PQL

Original Treatment Zone
Revised Treatment Zone

Figure A-8. (continued)

	E6		F4		E7		F5		E8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			1.64	0.58						
2 - 4					0.129	3.61				
4 - 6										
6 - 8									0.128 *	0.075 *
8 - 10	1.03	0.2565 *								
10 - 12										
12 - 14										
14 - 16					0.448 *	0.077				
16 - 18	0.39 *	0.093 *					0.462	0.562		
18 - 20							4.21	24		
20 - 22	3.46 *	27.55 *								
22 - 24										
24 - 26										
26 - 28					2.835 *	0.904				
28 - 30										

* The value to the left of this symbol is the practical quantitation limit (PQL). The PQL is provided because the fluoranthene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-8. (continued)

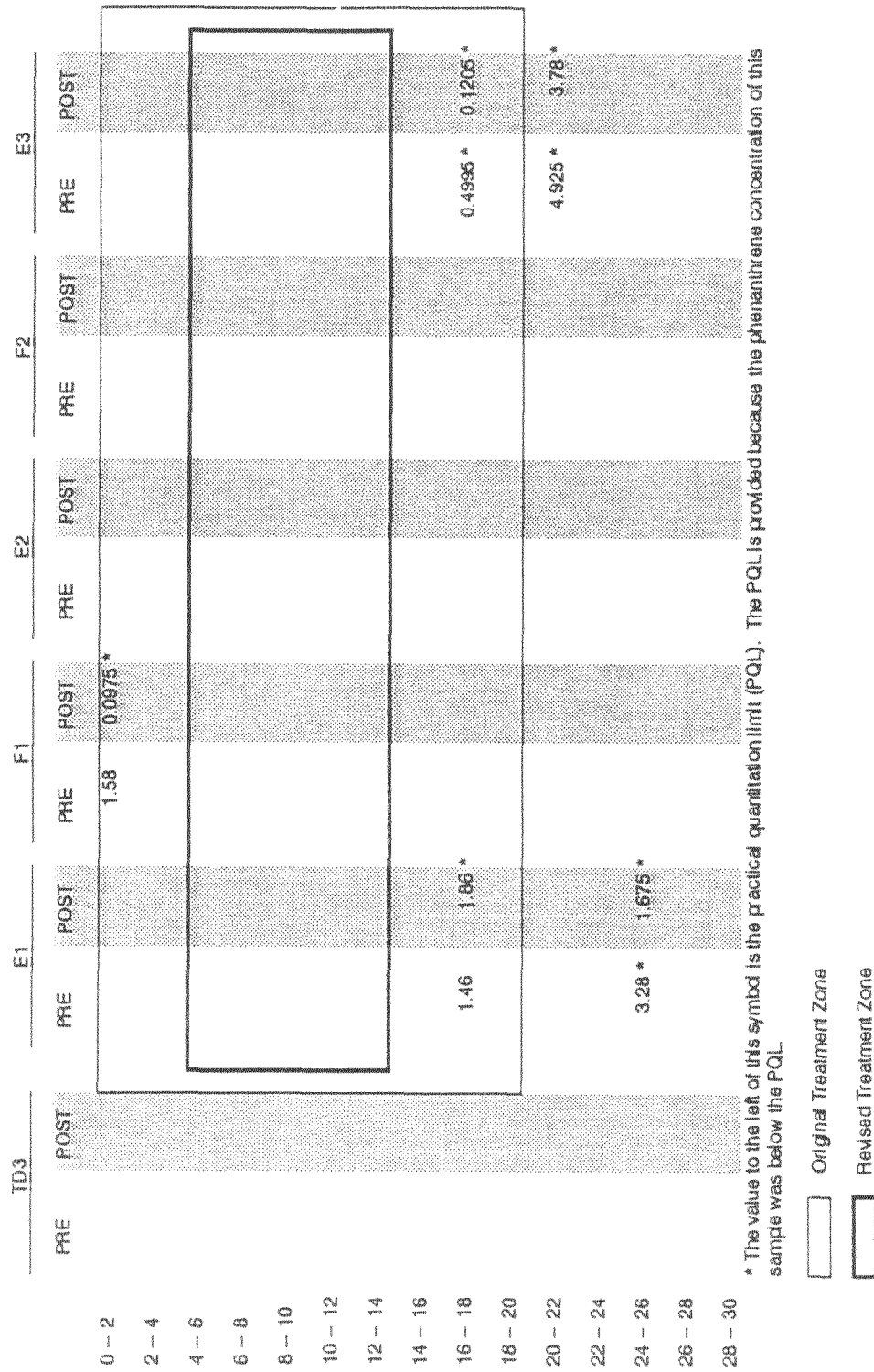


Figure A-9. Phenanthrene Concentrations (ppm).

	A1		E4		F3		E5		A2		TD6		TD5	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2	0.223	0.095 *							0.393	0.467 *				
2 - 4									0.506	0.294 *				
4 - 6							0.162 *	0.101 *	0.1355 *	0.133				
6 - 8							0.581	0.1 *						
8 - 10			0.65 *	0.665 *							0.159 *	0.121 *	0.1725 *	0.1205 *
10 - 12														
12 - 14														
14 - 16											0.478	2.63		
16 - 18									0.907 *	0.3735 *				
18 - 20	4.045 *	2.32 *											3.345 *	2.985 *
20 - 22														
22 - 24														
24 - 26			0.431 *	0.212 *					4.115 *	4.77				
26 - 28	3.25 *	0.308												
28 - 30														

* The value to the left of this symbol is the practical quantitative limit (PQL). The PQL is provided because the phenanthrene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-9. (continued)

	E6		F4		E7		F5		E8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			0.448	0.11 *						
2 - 4					0.1315 *	2.09				
4 - 6										
6 - 8									0.166 *	0.098 *
8 - 10	0.3915 *	0.3345 *								
10 - 12										
12 - 14										
14 - 16					0.58 *	0.1				
16 - 18	0.4365 *	0.121 *					0.607	0.736 *		
18 - 20							5.05 *	5.05		
20 - 22	3.875 *	35.95 *								
22 - 24										
24 - 26										
26 - 28					3.685 *	1.495				
28 - 30			0.364 *	1.86 *						

* The value to the left of this symbol is the practical quantiative limit (PQL). The PQL is provided because the phenanthrene concentration of this sample was below the PQL.

Original Treatment Zone
Revised Treatment Zone

Figure A-9. (continued)

Table A-9. Summary of SVOC Percent Decrease

Contaminant	Treatment Zone	Pretreatment Geometric Mean (ppm)	Post-treatment Geometric Mean (ppm)	Percent Decrease
Benzo(b)fluoranthene	Revised	.5271	.3168	40 ^c
	Original	.7653	.4315	44 ^d
	Outside Revised	.5907	.4669	— ^a
	Outside Original	.1908	.3046	— ^a
Benzo(a)anthracene	Revised	.2249	.1401	— ^a
	Original	.2969	.2181	— ^a
	Outside Revised	.2784	.1583	43 ^f
	Outside Original	.1157	.1024	— ^a
Benzo(a)pyrene	Revised	.2112	.1204	43 ^c
	Original	.3533	.1966	44 ^e
	Outside Revised	.5917	.3330	— ^a
	Outside Original	— ^b	— ^b	— ^b
Bis(2-ethylhexyl)phthalate	Revised	1.921	.5141	— ^a
	Original	5.752	2.593	55 ^f
	Outside Revised	9.372	7.861	— ^a
	Outside Original	5.362	8.239	— ^a
Chrysene	Revised	.3129	.1879	40 ^c
	Original	.3768	.2863	— ^a
	Outside Revised	.4071	.2971	— ^a
	Outside Original	— ^b	— ^b	— ^b
Pyrene	Revised	.5503	.2203	60 ^f
	Original	.5865	.3269	— ^a
	Outside Revised	.3597	.2373	— ^a
	Outside Original	.1229	.1491	— ^a
Fluoranthene	Revised	.5084	.2399	53 ^c
	Original	.8462	.6063	— ^a
	Outside Revised	1.368	.9958	— ^a
	Outside Original	1.309	1.188	— ^a

a Not accepted at an 80 percent confidence level.

b Value could not be determined.

c Accepted at a 80 percent confidence level.

d Accepted at a 97.5 percent confidence level

e Accepted at a 95 percent confidence level.

f Accepted at a 90 percent confidence level.

Table A-10. Summary of VOC Percent Decrease

Contaminant	Treatment Zone	Pretreatment Geometric Mean (ppb)	Post-treatment Geometric Mean (ppb)	Percent Decrease
Toluene	Revised	---- ^a	---- ^a	---- ^a
	Original	134.2	437.7	---- ^b
	Outside Revised	15,851	9,078	---- ^b
	Outside Original	12,715	7,547	---- ^b
Chlorobenzene	Revised	23.59	38.41	---- ^b
	Original	2,058	1,201	---- ^b
	Outside Revised	28,696	20,360	---- ^b
	Outside Original	37,326	53,265	---- ^b
Methylene Chloride	Revised	---- ^a	---- ^a	---- ^a
	Original	---- ^a	---- ^a	---- ^a
	Outside Revised	---- ^a	---- ^a	---- ^a
	Outside Original	---- ^a	---- ^a	---- ^a

a Due to the lack of matched pairs, the value could not be determined

b Not accepted at an 80 percent confidence level.

Table A-11. Sample Times for SVE System Sampling

Sample Date	System Condition
April 8, 1994	Vapor extraction system on, RFH yet to begin
May 6, 1994	RFH system on (since April 24, 1994)
May 31, 1994	Soil temperature at approximately 100°C in areas near operating antennae
June 7, 1994	Maximum soil temperature achieved just prior to RFH system being turned off
June 14, 1994	Soil cooling, vapor extraction system on
June 24, 1994	Just prior to vapor extraction system turn off

Table A-12. SVE System Conditions During Sampling

Date	$\Delta P(^{\circ}\text{H}_2\text{O})$	Pressure ($^{\circ}\text{Hg}$)	Temperature ($^{\circ}\text{F}$)	Moisture ¹	Duct Velocity (ft/sec)	ACFM ²	DSCFM ³
04/08/94	1.35	28.25	90	2.0	81.91	108.1	96.4
04/08/94	0.30	26.69	105	10.0	40.89	54.0	40.6
05/06/94	0.10	26.69	126	10.0	24.04	31.7	23.0
05/31/94	0.45	27.34	157	32.0	54.08	71.4	38.1
06/07/94	0.40	28.25	157	32.0	50.16	66.2	36.5
06/14/94	0.64	28.47	100	8.2	57.37	75.7	62.6
06/24/94	0.25	28.69	116	5.0	36.00	47.5	39.8

¹ Exhaust gas moisture content estimated based on duct temperature and moisture fraction based on saturation tables.

² Actual cubic feet per minute.

³ Dry standard cubic feet per minute.

Table A-13. SVOC Concentrations in the Vapor Stream

Compound	Sample Concentration ($\mu\text{g}/\text{m}^3$)					
	040894-R-009	050694-R-011	053194-R-016	060794-R-020	061494-R-023	062494-R-025
Acenaphthene	ND	22.3	ND	ND	ND	ND
Dibenzofuran	ND	8.7	ND	ND	ND	ND
1,2-Dichlorobenzene	998	17,000	23,400	24,800	928	14,500
1,3-Dichlorobenzene	322	1,480	2,230	2,060	80	1,880
1,4-Dichlorobenzene	1,122	3,880	6,430	7,030	271	6,020
Diphenylamine/N-NitrosDPA	ND	50.7	ND	ND	ND	ND
Fluorene	ND	10.2	ND	ND	ND	ND
2-Methylnaphthalene	10.2	147	59.1	83.2	0.7	ND
N-Nitroso-di-n-propylamine	ND	ND	83.7	ND	ND	ND
Naphthalene	14.7	221	166	177	3.4	ND
Phenanthrene	ND	24.0	ND	ND	ND	ND
1,2,4-Trichlorobenzene	4.1	124	ND	ND	3.9	ND

Table A-14. VOC Concentrations in the Vapor Stream

Compound	Sample Concentration (ppbv)					
	040894-R-007	050694-R-012	053194-R-014	060794-R-018	061494-R-022	062494-R-026
Ethane	98,700	114,000	16,300	31,300	6,490	122,000
Chlorodifluoromethane	ND	ND	ND	ND	ND	ND
Propane	ND	ND	609	ND	ND	ND
Chloromethane	ND	88.7	60.3	ND	ND	ND
Dichlorodifluoromethane	ND	ND	ND	ND	ND	16.3
Isobutane	ND	212	ND	ND	ND	340
Vinyl Chloride	34.5	14	10.8	10.5	ND	10.1
Isobutene + 1-Butene	ND	360	ND	ND	ND	158
n-Butane	353	623	307	ND	ND	1,160
t-2-Butene	ND	ND	ND	ND	ND	ND
Chloroethane	ND	ND	ND	ND	ND	ND
Isopentane	5,660	8,810	1,820	2,330	529	24,100
Acetone	ND	914	ND	ND	ND	ND
Trichlorofluoromethane	ND	ND	3.5	230	2.5	94.8
n-Pentane	2,240	2,980	715	785	215	8,690
1,1-Dichloroethylene	24.7	48.7	2.2	ND	ND	35.2
Methylene Chloride	ND	ND	3.5	14,000	32.2	81.1
2-Methyl-2-butene	ND	ND	93.5	ND	ND	ND
Neohexane	1,170	1,930	388	466	111	4,930
t-1,2-Dichloroethylene	ND	ND	ND	ND	ND	ND
1,1-Dichloroethane	ND	ND	ND	ND	ND	ND
Cyclopentane	516	552	124	155	35.2	1,640

Table A-14. (continued)

Compound	Sample Concentration (ppbv)					
	040894-R-007	050694-R-012	053194-R-014	060794-R-018	061494-R-022	062494-R-026
2,3-Dimethylbutane	2,610	2,530	643	837	174	6,770
MTBE, Isohexane, c-4-M-2-Pentene	3,360	2,600	719	898	196	8,460
3-Methylpentane	4,670	4,890	1,150	1,460	332	14,800
c-1,2-Dichloroethylene	133	33.1	78.7	100	7.9	103
n-Hexane	1,750	1,020	412	446	94.6	1,800
Chloroform	ND	ND	1.6	ND	ND	ND
Methylcyclopentane	2,600	1,580	561	703	149	4,960
1,2-Dichloroethane	ND	ND	ND	ND	ND	ND
2,4-Dimethylpentane	2,740	1,780	668	862	171	4,350
1,1,1-Trichloroethane	ND	62.9	5.3	21.4	ND	70.6
Benzene	3,900	1,480	1,420	1,840	295	6,980
1-Butanol + Cyclohexane	4,040	2,850	994	1,270	251	8,270
Isoheptane + 2,3-Dimethylpentane	5,450	3,250	1,400	1,820	341	8,060
3-Methylhexane	2,520	1,230	614	790	149	3,310
Trichloroethylene + BromoDCmethane	51.0	8	25.7	37.1	3.4	34.0
1,4-Dioxane + 2,2,4-Trimethylpentane	16,800	10,300	5,300	6,930	1,240	21,600
n-Heptane	873	215	326	388	51.7	635
Methylcyclohexane	7,080	3,660	1,980	2,690	465	13,000
Methylisobutylketone	847	759	246	335	67.1	1,620
2,5-Dimethylhexane	1,900	866	577	764	133	2,810
2,2,3-Trimethylpentane	2,470	1,410	803	1,050	183	3,670
1,1,1-Trichloroethane	ND	ND	ND	ND	ND	ND
2,3,4-Trimethylpentane	4,000	2,480	1,640	2,160	361	5,730

Table A-14. (continued)

Compound	Sample Concentration (ppbv)					
	040894-R-007	050694-R-012	053194-R-014	060794-R-018	061494-R-022	062494-R-026
Toluene	5,730	3,720	2,690	3,350	513	8,930
Dibromochloromethane	ND	ND	ND	ND	ND	ND
3-Methylheptane	1,100	458	387	520	82.3	1,460
Hexanal	3,290	2,030	1,190	1,580	274	6,870
1,2-Dibromoethane	ND	ND	ND	ND	ND	ND
2,2,5-Trimethylhexane	ND	1420	1030	1350	226	3,910
1-Octene	171	65.5	ND	73.6	ND	190
n-Octane	1,110	702	576	219	109	2,120
Tetrachloroethylene	8	14.3	21.6	35.7	3.5	62.3
Chlorobenzene	20,500	7110	12700	18600	2,800	40,400
Ethylbenzene	444	328	199	291	37	990
p-Xylene + m-Xylene	701	211	401	475	67.7	752
Bromoform	ND	ND	ND	ND	ND	ND
Styrene	613	183	ND	ND	ND	974
Heptanal	ND	ND	259	60.9	ND	254
1,1,1,2-Tetrachloroethane	ND	ND	ND	ND	ND	ND
o-Xylene	198	ND	38.6	114	ND	ND
n-Nonane	ND	93.9	260	326	40	103
Isopropylbenzene	175	98.3	107	128	19.9	438
<u>a-Pinene + Benzaldehyde</u>	771	256	423	550	80.5	1,710
n-Propylbenzene	302	102	ND	108	ND	1,680
m-Ethyltoluene	ND	101	145	182	ND	271
p-Ethyltoluene	428	191	308	393	56	1,290

Table A-14. (continued)

Compound	Sample Concentration (ppbv)					
	040894-R-007	050694-R-012	053194-R-014	060794-R-018	061494-R-022	062494-R-026
1,3,5-Trimethylbenzene	106	149	92.9	321	40.8	226
o-Ethyltoluene	ND	98.2	187	272	ND	102
b-Pinene	ND	173	ND	273	15.3	873
1,2,4-Trimethylbenzene	283	185	290	403	51.2	588
Benzyl Chloride + m-Dichlorobenzene	464	414	450	618	81.8	854
Isobutylbenzene	ND	66.1	ND	ND	ND	ND
n-Decane + p-Dichlorobenzene	470	765	1,470	2250	209	1,640
1,2,3-Trimethylbenzene	ND	ND	225	293	32.3	929
o-Dichlorobenzene	2,040	2,730	5,160	7280	964	5,010
Limonene	ND	ND	ND	ND	ND	339
Indene	ND	ND	135	ND	ND	ND
m-Diethylbenzene	188	106	126	263	ND	501
n-Butylbenzene	334	55.2	134	263	ND	589
p-Diethylbenzene	225	74.4	66.7	193	ND	594
n-Undecane	125	145	371	493	49.9	474
Naphthalene	ND	78.6	60.0	92.3	ND	138
Unidentified VOC	41,400	23,600	26,300	33,900	3,580	98,500
Unidentified Halogenated VOC	60	ND	6.0	ND	ND	96
TNMHC	191,000	137,000	86,400	117,000	17,000	391,000

Soil Vapor Analysis

Soil vapor was sampled and analyzed at six locations after the demonstration. Table A-15 summarizes the VOC concentrations in each of the soil vapor samples.

Groundwater

Table A-16 summarizes the pretreatment groundwater analytical results of samples taken from wells MW-10, MW-09, and DW-02. The groundwater was analyzed for TRPH, SVOCs, and VOCs.

A.2 Particle Size Distribution Analyses

Tables A-17 and A-18 present the results of particle size distribution analyses, which were conducted to characterize the soil. Particle size analyses were conducted using two techniques: dry-sieving and wet-sieving. The majority of the samples were just dry-sieved; however, a few samples were wet-sieved. Particle size distribution data from dry-sieving is presented in Table A-17 and particle size distribution data from wet-sieving is presented in Table A-18. For evaluation purposes, the data were simplified into three categories: gravel, sand, and fines. Particles that are less than 3 inches (7.62 cm) in diameter but will not pass through a #4 sieve (4.750 mm) are classified as gravel, particles that will pass through a #4 sieve but will not pass through a #200 sieve (0.075 mm) are classified as sand, and particles that will pass through a #200 sieve are classified as fines.

Contrary to what was expected, wet-sieving produced significantly different results than did dry-sieving. Discussions with laboratory personnel indicated that the two procedures should have yielded similar results. Since dry-sieving is less costly, and the use of dry-sieving was part of the approved Demonstration Plan, the decision to dry-sieve seemed to be sound. It appears, however, the sample preparation associated with the dry-sieved samples was not rigorous enough to break down many of the cohesive silt and clay particles into sizes that would pass the #200 sieve. The results from the dry-sieving probably do not reflect actual site conditions, and the percent sand data are likely to be lower and the percent fines correspondingly higher. As a result, only particle size distribution data from wet-sieving are being used to characterize the site. The data from dry-sieving are not being used.

Table A-15. Soil Vapor VOC Concentrations

Compound	Compound Concentration (ppbv)					
	040894-R-001	040894-R-002	040894-R-003	040894-R-004	040894-R-005	040894-R-006
Ethane	14,700,000	225,000	192,000	291,000	278,000	11,900
Chlorodifluoromethane	128	ND	ND	ND	ND	ND
Propane	ND	ND	ND	ND	ND	ND
Chloromethane	ND	ND	ND	ND	ND	ND
Dichlorodifluoromethane	311	ND	ND	ND	ND	ND
Isobutane	21,700	393	ND	ND	ND	ND
Vinyl Chloride	204,000	476	70.0	352	78.8	ND
Isobutene + 1-Butene	16,400	281	782	ND	1,400	ND
n-Butane	279,000	1,250	432	850	903	ND
t-2-Butene	12,200	ND	ND	ND	ND	ND
Chloroethane	312	ND	ND	ND	44.3	ND
Isopentane	2,190,000	13,500	7,920	16,300	19,500	184
Acetone	ND	ND	ND	ND	ND	ND
Trichlorofluoromethane	ND	ND	ND	ND	ND	ND
n-Pentane	277,000	1,990	2,550	2,720	6,090	ND
1,1-Dichloroethylene	3,150	200	95.3	241	207	195
Methylene Chloride	1,630	ND	81.8	19.8	ND	ND
2-Methyl-2-butene	ND	ND	ND	ND	ND	ND
Neohexane	18,500	506	457	349	1,020	ND
t-1,2-Dichloroethylene	50	ND	12.5	ND	29.0	ND
1,2-Dichloroethane	123	ND	36.6	ND	87.3	ND
Cyclopentane	36,900	413	924	634	1,930	ND

Table A-15. (continued)

Compound	Compound Concentration (ppbv)					
	040894-R-001	040894-R-002	040894-R-003	040894-R-004	040894-R-005	040894-R-006
2,3-Dimethylbutane	316,000	3,510	5,390	4,980	10,700	85.5
MTBE, Isohexane, c-4-M-2-Pentene	229,000	3,120	7,150	3,820	13,400	98.3
3-Methylpentane	120,000	2,590	5,410	4,320	9,500	70.0
c-1,2-Dichloroethylene	186,000	3,480	209	2,590	39.1	ND
n-Hexane	124,000	1,090	5,520	2,230	8,340	73.8
Chloroform	2,020	ND	ND	ND	ND	ND
Methylcyclopentane	79,100	2,990	10,000	3,490	13,900	100
1,2-Dichloroethane	1,540	25.6	ND	8.0	ND	ND
2,4-Dimethylpentane	157,000	2,780	9,050	3,660	12,400	92.3
1,1,1-Trichloroethane	ND	ND	ND	ND	ND	ND
Benzene	21,900	589	19,500	665	14,100	120
1-Butanol + Cyclohexane	77,100	3,320	15,500	4,280	18,700	148
Isoheptane + 2,3-Dimethylpentane	176,000	4,150	20,400	5,750	21,600	130
3-Methylhexane	40,400	1,320	11,100	1,490	11,300	81.5
Trichloroethylene + BromoDCmethane	90,400	613	63.2	740	9.6	ND
1,4-Dioxane + 2,2,4-Trimethylpentane	563,000	13,400	91,000	93,700	700	ND
n-Heptane	78,400	669	1,940	1,880	960	ND
Methylcyclohexane	87,400	5,820	40,100	6,710	33,300	260
Methylisobutylketone	ND	354	3,300	354	2,570	ND
2,5-Dimethylhexane	41,900	1,040	11,600	1,590	8,180	59.5
2,2,3-Trimethylpentane	48,100	1,420	13,700	2,060	10,100	77.9
1,1,2-Trichloroethane	89.5	38.6	ND	ND	ND	ND
2,3,4-Trimethylpentane	87,700	3,120	29,100	4,850	18,500	143

Table A-15. (continued)

Compound	Compound Concentration (ppbv)					
	040894-R-001	040894-R-002	040894-R-003	040894-R-004	040894-R-005	040894-R-006
Toluene	259,000	10,900	38,400	13,700	23,400	268
Dibromochloromethane	ND	19.7	ND	ND	ND	ND
3-Methylheptane	14,100	424	5,880	723	2,400	ND
Hexanal	20,200	1,770	20,900	1,970	11,000	61.2
1,2-Dibromoethane	8.5	48.0	ND	ND	ND	ND
2,2,5-Trimethylhexane	35,800	1,280	18,400	1,940	9,190	72.5
1-Octene	ND	ND	1,080	ND	523	ND
n-Octane	23,800	700	6,000	1,300	2,680	ND
Tetrachloroethylene	2,470	187	6.5	201	ND	ND
Chlorobenzene	42,800	11,700	168,000	7,950	44,900	583
Ethylbenzene	6,930	395	3,110	612	895	ND
p-Xylene + m-Xylene	22,000	1,240	1,220	2,730	679	61.3
Bromoform	ND	63.0	ND	ND	ND	ND
Styrene	ND	278	2,920	362	718	ND
Heptanal	ND	ND	ND	ND	ND	ND
1,1,2,2-Tetrachloroethane	ND	83.3	ND	ND	ND	ND
o-Xylene	6,070	708	792	924	215	ND
n-Nonane	17,100	134	617	713	123	ND
Isopropylbenzene	ND	119	1,910	181	271	ND
a-Pinene + Benzaldehyde	4,560	219	7,130	358	709	ND
n-Propylbenzene	ND	101	3,520	214	363	ND
m-Ethyltoluene	ND	238	494	604	ND	ND
p-Ethyltoluene	4,070	348	4,560	462	496	ND

Table A-15. (continued)

Compound	Compound Concentration (ppbv)					
	040894-R-001	040894-R-002	040894-R-003	040894-R-004	040894-R-005	040894-R-006
1,3,5-Trimethylbenzene	7,130	305	2,050	834	741	ND
o-Ethyltoluene	4,290	178	960	417	147	ND
b-Pinene	ND	ND	ND	ND	ND	ND
1,2,4-Trimethylbenzene	6,480	344	2,400	995	323	ND
Benzyl Chloride + m-Dichlorobenzene	28,900	8,230	2,680	5,850	653	62.1
Isobutylbenzene	ND	ND	ND	ND	ND	ND
n-Decane + p-Dichlorobenzene	76,900	14,800	2,840	11,500	738	81.4
1,2,3-Trimethylbenzene	ND	ND	ND	ND	ND	ND
o-Dichlorobenzene	441,000	122,000	8,610	90,600	1,300	393
Indene	ND	ND	ND	ND	ND	ND
m-Diethylbenzene	ND	77.4	4,120	ND	ND	ND
n-Butylbenzene	3,140	149	2,050	293	437	ND
p-Diethylbenzene	ND	181	1,170	196	224	ND
n-Undecane	8,680	316	1,010	688	173	ND
Naphthalene	ND	115	366	247	112	ND
Unidentified VOC	558,000	27,000	288,000	122,000	104,000	446
Unidentified Halogenated VOC	397	117	112	285	142	6.6
TNMHC	10,400,000	346,000	1,030,000	453,000	643,000	7,840

Table A-16. Summary of Groundwater Sampling Results

Well ID Number	Measurement	Result
MW-10	TRPH (mg/L)	4.92
	Volatiles (ug/L)	
	Acetone	61.9
	Benzene	782
	Chlorobenzene	25,500
	Trans-1,2-Dichloroethene	14.0
	Methyl ethyl ketone	16.4
	4-Methyl-2-Pentanone (MIBK)	11.5
	Toluene	51.2
	Vinyl Chloride	28.0
	Semivolatiles (µg/L)	
	2,4-Chlorophenol	36.3
	2-Chlorophenol	193
	1,2-Dichlorobenzene	11,200
	1,3-Dichlorobenzene	760
	1,4-Dichlorobenzene	2160
	2-Methylnaphthalene	16.2
	Naphthalene	121
	Phenol	22.3
	1,2,4-Trichlorobenzene	51.4
MW-09	TRPH (mg/L)	0.834
	Volatiles (ug/L)	
	Benzene	596
	Chlorobenzene	12,000
	Ethylbenzene	91.9
	Toluene	5.65
	Vinyl Chloride	10.2
	Xylenes	12.0
	Semivolatiles (µg/L)	
	2-Chlorophenol	37.4
	1,2-Dichlorobenzene	163
	1,3-Dichlorobenzene	23.5
	1,4-Dichlorobenzene	183
	2-Methylnaphthalene	59.2
	Naphthalene	71.1
	Phenol	3.58

Table A-16. (continued)

Well ID Number	Measurement	Result
DW-02	TRPH (mg/L)	267
	Volatile s(ug/L)	
	Chlorobenzene	15,500
	Semivolatiles (ug/L)	
	Acenaphthene	7.79
	2-Chlorophenol	22.1
	1,2-Dichlorobenzene	1820
	1,3-Dichlorobenzene	152
	1,4-Dichlorobenzene	529
	bis(2-ethylhexyl)phthalate	218
	Fluoranthene	29.3
	Fluorene	7.51
	2-Methylnaphthalene	124
	Naphthalene	86.8
	Phenanthrene	7.17
	1,2,4-Trichlorobenzene	15.5

Table A-17. Particle Size Distribution Data (Dry-Sieving)

Pretreatment				Post-treatment			
Sample ID	% Gravel	% Sand	% Fines	Sample ID	% Gravel	% Sand	% Fines
A1-U1820	65.3%	33.1%	1.6%	A1A-U0002**	35.4%	59.3%	5.4%
A1-U2728	35.0%	62.7%	2.3%	A1A-U1820	41.5%	50.2%	8.3%
A2-U0002**	27.4%	68.4%	4.3%	A1A-U2627	63.8%	34.6%	1.6%
A2-U0204	23.7%	74.3%	2.0%	A2A-U0002	35.8%	58.7%	5.5%
A2-U1214	23.4%	72.6%	4.0%	A2A-U0204	33.4%	63.3%	3.3%
A2-U1618	18.3%	79.3%	2.4%	A2A-U0406	34.0%	58.1%	7.9%
A2-U2022	5.6%	87.5%	6.9%	A2A-U1012**	33.4%	54.7%	12.0%
A2-U2628	79.1%	20.3%	0.6%	A2A-U1214**	20.2%	69.8%	10.1%
E1-U0002**	32.6%	64.0%	3.5%	A2A-U2022	29.6%	66.6%	3.8%
E1-U1012	36.9%	57.9%	5.2%	E1A-U0204	43.9%	54.9%	1.2%
E1-U1618	61.0%	36.4%	2.6%	E1A-U1618	51.4%	43.8%	4.8%
E2-U2628	67.3%	32.2%	0.5%	E1A-U2425	60.5%	38.1%	1.4%
E3-U1416	15.0%	81.6%	3.4%	E2A-U0204	51.7%	44.8%	3.5%
E3-U1618	8.2%	84.1%	7.7%	E2A-U1012	48.5%	48.6%	2.9%
E3-U2022	6.6%	85.9%	7.5%	E3A-U1416	42.7%	51.0%	6.3%
E4-U0709	11.2%	84.3%	4.5%	E3A-U1618	29.7%	61.2%	9.1%
E4-U0911	27.0%	61.6%	11.4%	E3A-U2022**	17.9%	73.0%	9.2%
E4-U2426	61.5%	34.4%	4.1%	E3A-U2830	59.5%	38.5%	2.0%
E5-U0406	23.5%	72.1%	4.4%	E5A-U0406	57.5%	37.3%	5.2%
E5-U0608	20.9%	72.8%	6.3%	E5A-U0608	27.8%	61.6%	10.6%
E5-U1012	32.2%	61.9%	5.9%	E5A-U1214	63.9%	33.5%	2.6%
E5-U1214	13.0%	77.8%	9.2%	E5A-U1820**	28.9%	63.4%	7.7%
E5-U1820	13.7%	80.3%	6.0%	E5A-U2022	29.6%	64.0%	6.4%
E5-U2022	29.7%	64.4%	5.9%	E6A-U0810	35.2%	62.2%	2.6%
E6-U0810**	33.3%	61.9%	4.9%	E6A-U1618	41.3%	54.5%	4.2%
E6-U2022	48.2%	48.6%	3.2%	E7A-U0204	58.1%	39.4%	2.5%
E7-U0204	50.9%	46.0%	3.1%	E7A-U1214**	33.0%	61.5%	5.6%
E7-U1214D	25.1%	63.8%	11.1%	E8A-U2426	77.8%	20.4%	1.8%
E8-U0608	33.4%	63.1%	3.5%	E8A-U2628	60.7%	37.4%	1.9%
E8-U2426	66.7%	30.8%	2.5%	F1A-U1820	37.0%	56.5%	6.5%
E8-U2628	51.2%	45.4%	3.4%	F2A-U2628	65.9%	33.5%	0.6%
F1-U1012	14.8%	79.8%	5.4%	F3A-U0406	48.4%	45.0%	6.6%
F1-U1820	53.7%	40.1%	6.2%	F4A-U0002	45.2%	51.9%	2.9%
F2-U1416	7.7%	84.2%	8.1%	F4A-U1214	34.2%	63.5%	2.3%
F2-U2628	59.1%	38.5%	2.4%	F4A-U1618	15.9%	77.8%	6.3%
F3-U0406	40.1%	55.6%	4.3%	F4A-U2830	69.8%	29.1%	1.1%
F3-U1012	20.8%	72.0%	7.2%	F5A-U1214	38.8%	58.4%	2.8%
F4-U0002	36.2%	59.2%	4.6%	F5A-U1618	44.8%	51.5%	3.7%
F4-U1214	21.4%	67.9%	10.7%	F5A-U1820	40.7%	53.1%	6.2%
F4-U2829	73.1%	25.4%	1.5%	F5A-U2224	56.9%	40.6%	2.5%
F5-U1214	19.1%	73.2%	7.7%	TD3A-U0608	52.7%	45.0%	2.3%
F5-U1618	25.5%	67.4%	7.1%	TD3A-U1416	25.8%	71.0%	3.2%
F5-U1820	27.2%	67.1%	5.7%	TD3A-U2426	73.7%	25.1%	1.2%
TD3-U1416**	45.5%	49.4%	5.2%	TD5A-U1416	61.5%	33.8%	4.7%
TD3-U2426	67.7%	30.1%	2.2%	TD6A-U0406	43.6%	53.7%	2.7%
TD5-U0406	31.2%	62.1%	6.7%	TD6A-U1416	50.6%	44.4%	5.0%
TD5-U1416	25.2%	69.1%	5.7%	Average	44.6%	50.8%	4.6%
TD5-U2425	55.9%	43.4%	0.7%				
TD6-U0406	36.2%	58.3%	5.5%				
TD6-U2426	62.3%	36.8%	0.9%				
Average	35.4%	59.8%	4.8%				

*Particle size distributions determined by dry-sieving were significantly different than those determined by wet-sieving.

** Average of two duplicate analyses.

Table A-18. Particle Size Distribution Data (Wet-Sieving)

Pretreatment				Post -treatment			
Sample ID	% Gravel	% Sand	% Fines	Sample ID	% Gravel	% Sand	% Fines
A2-U0002	34.4%	29.5%	36.1%	A2A-U1618	42.5%	27.0%	30.5%
A2-U0406	19.2%	48.0%	32.8%	E1A-U0204	43.7%	33.2%	23.1%
A2-U1012**	22.9%	34.3%	42.8%	E5A-U1012	29.6%	23.9%	46.5%
E2-U1012	19.8%	30.3%	49.9%	E8A- U0608	43.6%	26.9%	29.5%
E3-U2830	44.8%	38.3%	16.9%	TD5A- U0406	47.5%	30.5%	22.0%
E6-U1618	32.7%	19.5%	47.8%	TD6A – U2627	50.2%	32.9%	16.9%
E7-U1214**	5.2%	21.3%	73.6%	Average	42.9%	29.1%	28.1%
F5-U2324	56.5%	24.5%	19.0%				
Average	29.4%	30.7%	39.9%				

- Particle size distributions determined by dry-sieving were significantly different than those determined by wet -sieving.
- ** Average of two duplicate analyses.

A.3 Moisture Data

Moisture analyses were conducted so that soil sample concentration results could be converted to dry weight results. Figure A-10 presents the results of moisture analyses in the same format used to present the results of the chemical analyses. Based on the final statistical evaluation, there were statistically significant decreases in percent moisture inside the original and revised treatment zones. Moisture results for all zones are summarized in Table A-19.

Table A-19. Summary of Percent Moisture Results

	Estimated Change in Mean Concentration	Confidence Level
Inside Original Treatment Zone	-53 %	> 99.9%
Inside Revised Treatment Zone	-70%	>99%
Outside Original Treatment Zone	+ 19%	>95%
Outside Revised Treatment Zone	**	**

= Did not exhibit a statistically significant change at 80% confidence level.

	TD3		E1		F1		E2		F2		E3	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			18.9	22.6			22.1	10				
2 - 4												
4 - 6	19.2	16.2			14.8	5.79						
6 - 8												
8 - 10												
10 - 12			12.5	23.3	25.6	3	26.2	17.9				
12 - 14												
14 - 16	19.2	20.8							30.2	8.38	22.3	26.7
16 - 18			6.89	18.3							20.7	23.8
18 - 20												
20 - 22					21	27					24.9	28.2
22 - 24												
24 - 26	12.3	19	6.01	9.31								
26 - 28							15.1	10.2	16.7	9.07		
28 - 30											5.94	18



 Original Treatment Zone
 Revised Treatment Zone

Figure A-10. Moisture content.

	A1		E4		F3		E5		A2		ID6		ID5	
	PRI	POST	PRI	POST	PRI	POST	PRI	POST	PRI	POST	PRI	POST	PRI	POST
0 - 2	18.5	2.98							18.8	1.18				
2 - 4									20.4	5.95				
4 - 6					16.6	16	16.7	9.07	18.6	0.4	14.8	24	22	23.9
6 - 8			16	10.1			15.6	7.86						
8 - 10			14.8	6.31										
10 - 12					20.5	4.15	18	2.39	22.3	0.2				
12 - 14							21.2	20.8	28	0.79				
14 - 16											15.1	13.7	15	20.8
16 - 18	24.2	21							19.9	26.7				
18 - 20	19.3	21.4					23.3	24.7						
20 - 22							25.6	21.4	22.9	26.7				
22 - 24														
24 - 26													8.47	9.92
26 - 28	5.16	6.99	7.6	14.1					9	14.9	8.73	16.2		
28 - 30														

Original Treatment Zone
Revised Treatment Zone

Figure A-10. (continued)

	E6		F4		E7		F5		E8	
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
0 - 2			19.5	16.8						
2 - 4					16	23.5				
4 - 6										
6 - 8									18.9	6.39
8 - 10	16	17.3								
10 - 12										
12 - 14			24.5	25.9	24.1	27	24.2	2.59		
14 - 16					30.2	8.38				
16 - 18	24.3	24	26.7	28.1			20.2	20.8		
18 - 20							24	20.8		
20 - 22	18.9	25.9								
22 - 24							11.3	4.9		
24 - 26							13.4	9.72		
26 - 28					11.6	13.2	9.44	14.5		
28 - 30			8.5	11						



 Original Treatment Zone
 Revised Treatment Zone

Figure A-10. (continued)

A.4 Operational and Process Data

Operational data for the KAI RFH SITE Demonstration was collected primarily by KAI and by the USAF contractor, B&RE. Operational data collected by B&RE and KAI were not independently verified by the SITE Program or its contractors. Table A-20 summarizes extraction well pressures and temperatures during the demonstration. Table A-21 summarizes the compressor and flare flow rates during the demonstration.

Table A-20. Summary of Operating Conditions Data

Well	Minimum Pressure (in. H ₂ O)	Maximum Pressure (in. H ₂ O)	Minimum Temperature (°C)	Maximum Temperature (°C)
E1	-17.0	0	18.9	36.6
E2	-30.0	0	19.8	60.7
E3	-30.0	0.1	19.4	45.3
E4	-49.0	-0.4	18.1	93.5
E5	-72.1	0	23.3	93.5
E6	-3.3	-0.3	19.5	31.7
E7	-3.8	0	19.5	31.3
E8	-4.6	0	19.7	31.4

Table A-21. Summary of Compressor and Flare Flow Rates

Component	Minimum Flow Rate (scfm)	Maximum Flow Rate (scfm)
Compressor	35	70
Flare	50	140

A.4.1 Temperature

Soil temperatures within and outside the revised treatment zone were indirectly monitored at various depths throughout the demonstration. The demonstration system was designed to heat the soil in the revised treatment zone to a temperature range of 100 to 130°C. Soil temperatures within and outside the revised treatment zone were monitored at various depths throughout the demonstration using

thermocouples, infrared temperature sensors, and fiberoptic temperature probes. All temperature measuring devices were mounted in lined boreholes, which made direct readings of the soil temperature impossible. The developer claims that actual soil temperatures were higher than the measurements indicate; however, this difference cannot be quantified. The maximum measured temperature on the perimeter of the revised treatment zone was 61°C. The maximum measured temperature near the center of the revised treatment zone was **234°C**, but this peak was not representative of the majority of the temperature measurements at this location. During most of the heating period, temperatures between 100 and 150°C were measured near the antenna to which energy was being applied. Although not observed during the demonstration, the developer claims that temperatures will become more uniform after all moisture is removed from around the antennae.

A.4.2 Residuals

Condensate from the vapor treatment system was pumped into a 500-gallon truck-mounted tank during the KAI RFH SITE demonstration. The condensate was transferred to the Kelly AFB Environmental Pollution Control Facility for treatment and discharge. Approximately 2,000 gallons of condensate were collected from the vapor treatment system during the KAI demonstration.

All soil cuttings were drummed and transferred to the Kelly AFB Drum Lot for disposal. Soil cuttings filled 40 drums during pretreatment sampling and 35 drums during post-treatment sampling. One drum filled with miscellaneous solid wastes (PPE, plastic sheets, etc.) was also transferred to the Kelly AFB Drum Lot for disposal.

A.4.3 Utilities

According to measurements taken by KAI, 15,749 kW of RF energy were delivered to the soil during the demonstration. Based on a 90 percent delivery efficiency, KAI estimates that 17,351 kW of RF energy were generated by the RF source. KAI further estimates, based on a 65 percent conversion efficiency, that 26,693 kW of AC electric power were consumed by the RF source. Total electric consumption for the site was measured during the demonstration. The B&RE project report states that 36,053 kWh of electricity were consumed during the project.

A.4.4 RF Emissions and Electric Field Measurements

RF emissions were measured with a broad band, vertically polarized, 2-meter high, calibrated, biconical antenna. The antenna signal was processed by a portable calibrated spectrum analyzer. Initial and closing measurements were witnessed by representatives of the Kelly AFB frequency management office. Detailed tests were logged on May 3, 18, and **24**, 1994 and on June 6, 7, 8, and 10, 1994.

The first through sixth harmonics of the operating frequency were measured in compliance with FCC part 18.305(b). Part 18.305(b) specifies a harmonic emission limit of 169 uV/m or 44.58 dB-uV/m at a distance of 300 m for the operating frequency of 27.12 MHz. Harmonics were measurable 10 meters from the active antenna but were typically unmeasurable or at the threshold of detection 300 meters from the active antenna. On June 7, with the RF generator operating at 23.21 kW, the second harmonic was detected at 2 uV/m or 3.90 dB-uV/m, which is easily within the FCC emission limit.

In addition to the harmonics, fundamental frequency emission levels (27.12 MHz) were measured in compliance with USAF requests. Surface emissions 10 m from the active antenna were typically about 0.4 V/m when the RF generator was operating at 20 kW. The highest surface emission measured 10 m from the active antenna was 1 V/m during an RF generator output power level of 23.56 kW. The highest surface emission measured 300 m from the active antenna was 0.25 V/m during an RF generator output power level of 23 kW.

The electric field at the site was measured with the calibrated electric and magnetic probes of a broad-band isotropic field strength meter. Electric field measurements were taken at defined locations on 23 heating days. Initial measurements were witnessed by Kelly AFB site safety personnel.

The site safety plan required maintaining the 6-minute average electric field exposure level for site personnel below 70 V/m. The permissible exposure limit (PEL) of 70 V/m was calculated for the 27.12 MHz operating frequency using a formula from AFOSH Standard 161-9, February 12, 1987. Electric field measurements are summarized in Table A-22.

The only electric field measurements that exceed 70 V/m were taken 0.1 m from the antenna. The electric field strength that close to the antenna is not believed to represent a risk to incidental human exposure. In addition, two red warning lamps, which were controlled directly by the RF generator's power enabling circuitry, alerted site personnel when the RF generator was operating.

Table A-22. Summary of Electric Field Measurements

Distance from Active Antenna	Range of Electric Field Measurements
0.1 m	25 to 132
1 m	7 to 59.1 V/m
3 m	1 to 14 V/m
10 m	up to 1 V/m

APPENDIX B

CASE STUDIES

B.1 SAVANNAH RIVER SUPERFUND SITE

The objective of the demonstration was to investigate the effectiveness of the KAI RFH system as an enhancement to vacuum extraction of residual solvents (primarily trichloroethylene and perchloroethylene) held in vadose zone clay deposits approximately 40 feet below the surface at the Savannah River Super-fund site. The KAI RFH system is mounted in an 8 ft x 8ft x 20 ft shelter that is mobilized by a 28-foot flatbed trailer and a 1-ton pickup truck. The system was configured for was provided by a diesel generator [1].

The demonstration integrated RF antenna technology and vacuum extraction from a single, horizontal well. The horizontal well was continuously screened over a 300-foot horizontal section. The antenna, approximately 17 feet long, operated at a maximum power output of 2 kW and a frequency of 13.56MHz. The antenna was inserted to a location approximately 100 feet from the start of the screened zone to heat one section of the well. The vacuum extraction system consisted of a rotary lobe blower capable of providing a flow of approximately 150 cubic feet per meter (cfm) at 6 inches Hg vacuum. Several vertical boreholes were placed both in and adjacent to the expected heat control zone to monitor temperatures, pressures, and soil gas concentrations. Approximately 11,000 kWh subsurface sediments and heated a soil volume of nearly 1500 cubic feet to temperatures greater than 60°C. The total volume heated to temperatures above ambient (20°C) was calculated at nearly 30,000 cubic

Several problems were encountered during the demonstration. Well flooding occurred due to residual water or near saturated soil conditions in the proximity of the screen. The well flooding resulted from heavy rainfall encountered during the first half of the test period. The system also experienced a low vapor flow which was a result of the low permeability and high water content of the clay. A vapor lock formed down hole at the antenna from steam generated by the RF condensation from the gas stream through the long transition to the surface were also encountered in this demonstration [1].

Over 170 kilograms of chlorinated solvents were successfully extracted from the sediments over the course of the demonstration. However, since the RFH system did not perform optimally, definite conclusions as to whether the technology enhanced the contaminant extraction cannot be drawn. Results show that any new system design should use extraction wells that are independent from the well used for RF application. It was concluded that extraction wells could be horizontal or vertical but should be located both within and on the perimeter of the zone anticipated to be heated by the RF antenna [1].

B.2 PILOT-SCALE TREATMENT OF SOIL CONTAMINATED WITH #2 FUEL OIL

A pilot-scale study was conducted to evaluate the ability of the KAI RFH system to enhance the removal of #2 Fuel Oil from silty soil. The water table was located at 22.5 feet bgs and the layer of contaminated soil extended from approximately 17.5 feet bgs to 22.5 bgs. An SVE system was in use at the site prior to the KAI test. At the initiation of treatment, the SVE system yielded recovery rates of thousands of gallons of oil per hour. The decrease of recovery rates to hundreds of gallons of oil per month prompted an evaluation of the ability of RFH to enhance the SVE product recovery rates [2].

Bench-scale testing indicated that substantial oil recovery could be expected at a soil temperature of 130°C. KAI also conducted “low-power” RF tests to characterize the soil, then designed a site-specific RF antenna to transfer RF energy into the contaminated soil. Subsequent “high-power” tests used this RF antenna and the existing SVE system in conjunction with KAI’s 25kW, 13.56-MHz, mobile RFH system. The RFH system was cycled on and off to maintain a temperature of 150°C or less in the antenna borehole. The test lasted 2 weeks and 8,000 kWh of power were applied to the contaminated soil during the test [2].

At the completion of the high-power test, the soil temperature was measured at four points within the zone of contamination. Two feet from the RF antenna, the temperature was approximately 80°C at 19 feet bgs and approximately 70°C at 21 feet bgs. Four feet from the antenna, the temperature was approximately 65°C at 19 feet bgs and approximately 75°C at 21 feet bgs. In addition, the fluid saturation of the soil was measured before and after KAI’s RFH test. The results of the fluid saturation measurements, which are presented in Table B-1, appear inconclusive [2].

Table B-1. Fluid Saturation of the Soil [2]

Depth, feet	<u>Percent Pore Oil</u>		<u>Percent Pore Water</u>	
	Before RFH Test	After RFH Test	Before RFH Test	After RFH Test
17	NA	1.0	NA	16.6
19	NA	3.5	NA	4.7
21	NA	6.6*	NA	9.0*
22	6.5	6.7	31.1	3.0
23	36.5	21.5*	53.1	70.0*
24	9.6	NA	77.3	NA
25	17.9	1.6	66.5	92.4

* Value is the average of two measurements (all other values are **from** single measurements).

NA = not analyzed

B.3 REFERENCES

1. Final Report: In Situ Radio Frequency Heating Demonstration. Westinghouse Savannah River **Company**. Revision 0. Aiken, SC.
2. Price, S.L., R.S. Kasevich, and M.C. Marley. Enhancing Site Remediation through Radio Frequency Heating. Preprint to be presented at the Eighth Annual Conference on Contaminated Soils - Moving Towards Site Closures. Presented by CHESS (Council for the Health and Environmental Safety of Soils), University of Massachusetts at Amherst, September 23, 1993.

Appendix C
Vendor Claims Section
for
Innovative Technology Evaluation Report

March 1995

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Introduction to In-situ RF Heating for SVE Enhancement

The radio frequency (RF) heating (RFH) process discussed in this document is based on the use of an antenna' technology to efficiently and specifically apply electromagnetic energy to a soil matrix. The focused electromagnetic energy pattern from the antenna heats the soil by directly interacting with the soil components at the molecular level. The RF energy desorbs and mobilizes the hydrocarbon contaminants and water by a very efficient direct heating action that does not ***require any soil permeability for energy propagation***². ***The*** mobilization of the hydrocarbons and water can significantly increase the permeability of the soil matrix and in some cases can create permeability'. Soil can be heated in a controlled manner to temperatures above 400 degrees C by RF energy.

The soil vapor extraction (SVE) process is dependent on the ambient vapor pressure of a contaminant in the soil and the permeability of the soil. The success of the SVE process is dependent on the flow of air through the soil matrix which is directly determined by its permeability. The addition of heat to the soil strongly volatilizes and mobilizes the contaminants that can be removed from the soil by the extraction air flow. The heat also increases soil permeability by the mobilization

¹ Traditional RF heating technology relies on placing the material to be heated between two conductive plates or metal rod grids that form a capacitor cell. Typically these plates are five to 15 foot square and separated by three to 20 feet, depending on the operating frequency of the RF energy. The KAI technology uses a dipole antenna structure that resembles a single pipe, several inches in diameter. The length is dependent on the operating frequency. Typical frequencies used for RF heating provide for antennas ranging in length from six to 20 feet which allow for the treatment of comparable soil thicknesses.

² RF energy propagates easily through dielectric materials such as dry soil. Wet or hydrocarbon impregnated soils absorb RF energy until the water and hydrocarbons are volatilized and driven from the soil. As the soil dries and is decontaminated the RF energy passing through the soil losing less energy and therefore more strongly heats the soil at a greater distance from the antenna.

³ The production of steam from water bound in some rocks is typically adequate to cause explosive fracturing which is a macroscopic permeability enhancing mechanism.

of water and some types of contaminants. Therefore, RFH enhances two of the governing mechanisms of the SVE process. Therefore, active in-situ RFH can be expected to dramatically shorten the SVE system closure time and improve recovery efficiency in comparison to that of a passive system.

Soil heating by steam or hot air injection are considered competitive processes to RFH. Both injection techniques require a minimum level of soil permeability for successful application. Heat is transferred into the soil by fluid propagation and thermal conduction mechanisms. Both processes require the use of high levels of energy generation and transmission to deliver relatively low levels of predictable heat to the subsurface environment due to significant thermal losses in the propagation process and the uncertainty of the fluid propagation paths within the soil matrix. Steam injection is limited to the delivery of temperatures below 100 degrees C and requires a removal and disposal strategy for the contaminated condensate. Hot air injection does not suffer this drawback but does not carry as high a level of thermal energy level into the formation as steam does. Both thermal injection approaches have been shown to be of value to remediation efforts. However, neither technique provides the precision and controlled delivery of heat that is available through RFH techniques.

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COMMENTS ON THE KELLY PROGRAM

The five sections presented here have been adapted entirely or in part from a December 1994 draft of a technical appendix⁴ supplied by KAI Technologies to Brown and Root Environmental. This technical appendix was written for inclusion in the final program demonstration report to the Air Force Center for Environmental Excellence.

1.0 PROGRAM SUMMARY

1.1 Overview

KAI Technologies, Inc. demonstrated its emerging in-situ radio frequency heating (RFH) process at Kelly Air Force Base, San Antonio, Texas, IRP site S-1 during the spring of 1994. The technology demonstration was conducted under contract with HalliburtonNUS⁵ under contract with the Armstrong Laboratory, Environics Directorate, AL/EQW, Tyndall Air Force Base in cooperation with the U.S. Environmental Protection Agency.

The primary objective of the RFH test of the KAI technology was to provide useful information to assist the Air Force in preparing for a commercial scale demonstration of RFH decontamination. This effort included the qualitative evaluation of vapor extraction and soil heating, the evaluation of contaminant movement through soil, and the removal of volatile organic compounds from the soil through the vapor stream. An important aspect of the program was to document RFH applied with a single borehole, dipole antenna, in contrast to previous RFH testing that used a cage of electrodes to form a capacitor heating cell.

Other important objectives of this test were: 1) validation of electromagnetic and thermal modeling; 2) demonstration of dual heating applicator (antenna) interactions during the heating cycle as a diagnostic tool; 3) documentation of safe near-field electromagnetic emission levels; 4) documentation of compliance with harmonic interference levels set by the Federal Communications Commission (FCC) for systems operating under part 18 rules.

The RFH test of the KAI technology was not a remedial action test. The soil vacuum extraction (SVE) system test used in the RFH demonstration was an experimental design with a number of unique operating configurations. The SVE system was operated with numerous configurations and was not optimally designed or operated for the heating pattern developed by the KAI heating antennas. Funding limitations did not allow the SVE portion of the RFH program to be explored and optimized. Therefore the absolute TRPH, VOC and SVOC removal rates measured versus the applied RF energy for this program cannot be used as statements on the effectiveness of RFH.

⁴ "RF System Operating Description- Appendix to the final program report," for the report titled, *Technology Demonstration of Radio Frequency Soil Decontamination*, submitted to Brown and Root Environmental for delivery under USAF Contract No. F33615-90-D-4011, Delivery Order No. 0007, contract Project No. 3688. December 1994 Draft submission.

⁵ Currently identified as Brown and Root Environmental, a Division of the Halliburton Corporation.

The KAI mobile RF system was prepared and ready to start heating within six working days of the system's arrival on site. The KAI RFH system successfully delivered 15,549 kilowatt hours of energy to the heating zone within a total time span of 5 1.3 days. The efficiency of the RF energy transfer to the soil during the heating period exceeded 85%. These are significant operational achievements that are prerequisites for commercial system development.

A dual antenna system was employed for this test. Measurements of mutual coupling between antennas during the heating periods provided information on the removal trends of moisture and contaminants. Significant changes in the mutual coupling measurements occurred during the heating periods. Refinement of this measurement technique will be an important diagnostic and control component of a fully automated commercial system.

The program accomplishments summarized below are from the perspective of the RFH system operation and interaction with site conditions.

1.2 Accomplishments

- The uniformity of soil heating within test volumes - The heating program provided an extensive data set of temperature profiles.

The initial heating rate of the test and several aspects of the SVE configuration produced thermal records that suggest that there are significant regions of uniformity with soil temperatures elevated well above 100 degrees centigrade (C).

There were regions, at a 3-foot radius from the antenna that exceeded 120 degrees C, even ***in the context of SVE flow influences*** (see section 4.0 of this document). These infrared (IR), indirect temperature profiling measurements suggested that adjacent soils should have had localized heating temperatures for the hydrocarbons at or above the 150 degree temperature goal of the program. The highest measured temperature for the program was a direct, peak measurement of 233.9 degrees C by a fiber optic temperature probe located on the outside of the heating well liner wall. The sustained high temperature readings in this region suggested a flow of a hot liquid into the volume surrounding the well liner sensor. This indirect measurement suggested that a significant mass of liquid was heated to a temperature in the vicinity of 240 degrees C within the heating zone.

- Commercial Operation - The later portion of the heating program (21.3 days) provided operating statistics that can be used for commercial system cost and operation projections. System costs for an automated, low labor requirement, system can be developed from the optimum operation periods of the program.

1.3 Modifications to Program Cost and Operation

This program was executed within the framework of several modifications. The most significant are:

- The on-site heating zone was defined as one-half of the volume originally planned as the treatment zone. This was due to the choice of a 27.12 MHZ frequency to heat two

thinner, 10-foot thick, adjacent volumes faster than the 13.56 MHz alternative **ISM**⁶ frequency. The 13.56 MHz frequency would have required more on-site heating time but would have covered the original, 20-foot thick treatment zone. The lower frequency also would have extended the volume of heating influence further beyond the SVE extraction and injection wells. Therefore, the collection efficiency of the SVE system, as installed, would have been increased.

- The RFH applicators were positioned high in the well liner borehole spanning from 4 feet down to 14 feet within the heating zone. Program time was not available to move the applicator to additional heating positions.
- Initial delivery of 3-phase AC utility power to the RFH system limited the RF energy generation rate. For the first 22 days of the program the system generated RF energy at an average rate of 9.42 kW/hr as opposed to the last 21.3 days that maintained generation at an average rate of 19.93 kW/hour.
- The initial low power delivery rate did not allow the sequential heating of boreholes A1 and A2 in a manner that would allow their heating patterns to overlay as an approximation of a dual applicator, dual RF generator system operated as a phased array.
- The design of the SVE system prevented meaningful conclusions being drawn about the measured changes in TRPH VOC and SVOC concentrations inside and outside the treatment zone as a result of RFH treatment.

1.4 Conclusions

Site set-up time was relatively fast and efficient with a 2-person KAI field team. The KAI mobile RF system performed as expected and provided significant RF energy coupling to the soil. The applicator system (antennas) allowed for flexibility in the in-situ application of RF energy at selected depths. The coupling efficiency or energy transfer to soil surrounding the antennas was high (> 85%). The application of energy to the heating zone increased the permeability of the zone by a factor of more than **20**⁷. This result has significant implications for commercial RFH systems operating with tight soils. SVE efficiency appeared to increase substantially during the demonstration period.

⁶ ISM is an abbreviation for the Industrial Scientific and Medical frequencies authorized for RF heating under the part 18 regulations of the Federal Communications Commission.

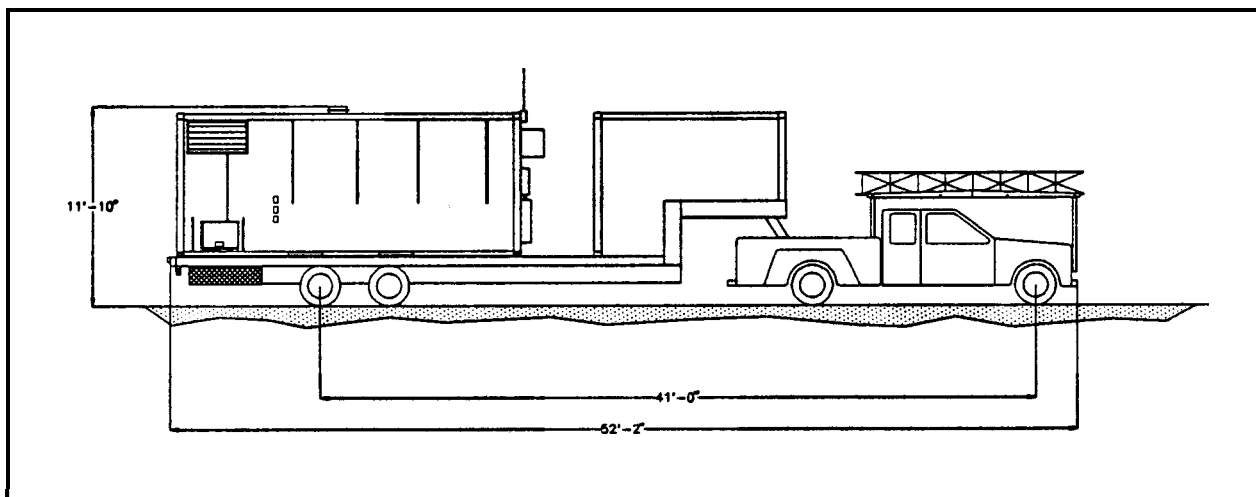
⁷ This is believed to be a conservative number. Factors of 50 can be derived from the data set but SVE conditions are not directly comparable for all calculations.

2.0 DETAILS OF THE BASIC RFH SYSTEM

The KAI RFH system is mobilized as a self-contained field unit with work space and storage capability to support two heating applicators. Figure 1 is a side view of the mobile system. The overall length is 52 feet and 2 inches with a trailer bed length of 28 feet. Figure 2 outlines the component groups of a basic radio frequency (RF) heating system. The system power is supplied from the local utility power grid or a diesel generator through the 3-phase power distribution panel. The panel supplies power to the RF generator and a cooling blower as well as lighting, air conditioning and instrumentation. The power system also includes an uninterruptable power supply for critical instrumentation and control functions. The RF Generator supplies power through the transmission lines and the matching network to the RFH applicator or "antenna" which typically radiates 95% of the energy it receives into the surrounding medium (soil, rock, oil).

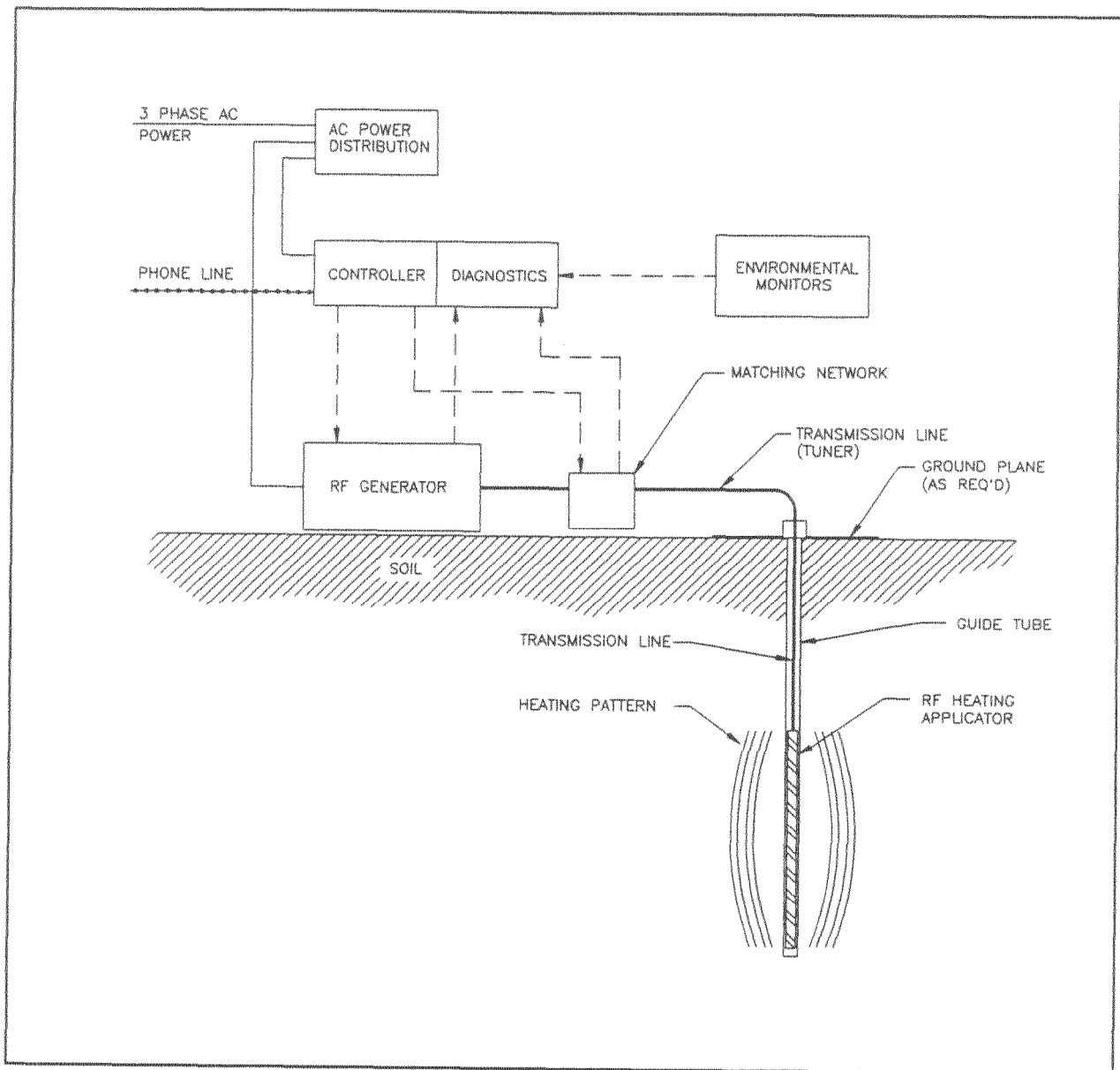
The system controller is interfaced to all elements of the system. Site environmental monitors can detect overheated components, energy leakage and component tampering. The controller is capable of transferring the complete monitoring of the system to a remote location through a phone line or a cellular telephone data link.

Alarms and system status messages can be set via the telephone link or messages can be sent as pre-recorded voice segments via the same UHF radio frequency transceiver used for site communications. On-site diagnostics instruments periodically measure the system's performance and verify operation.

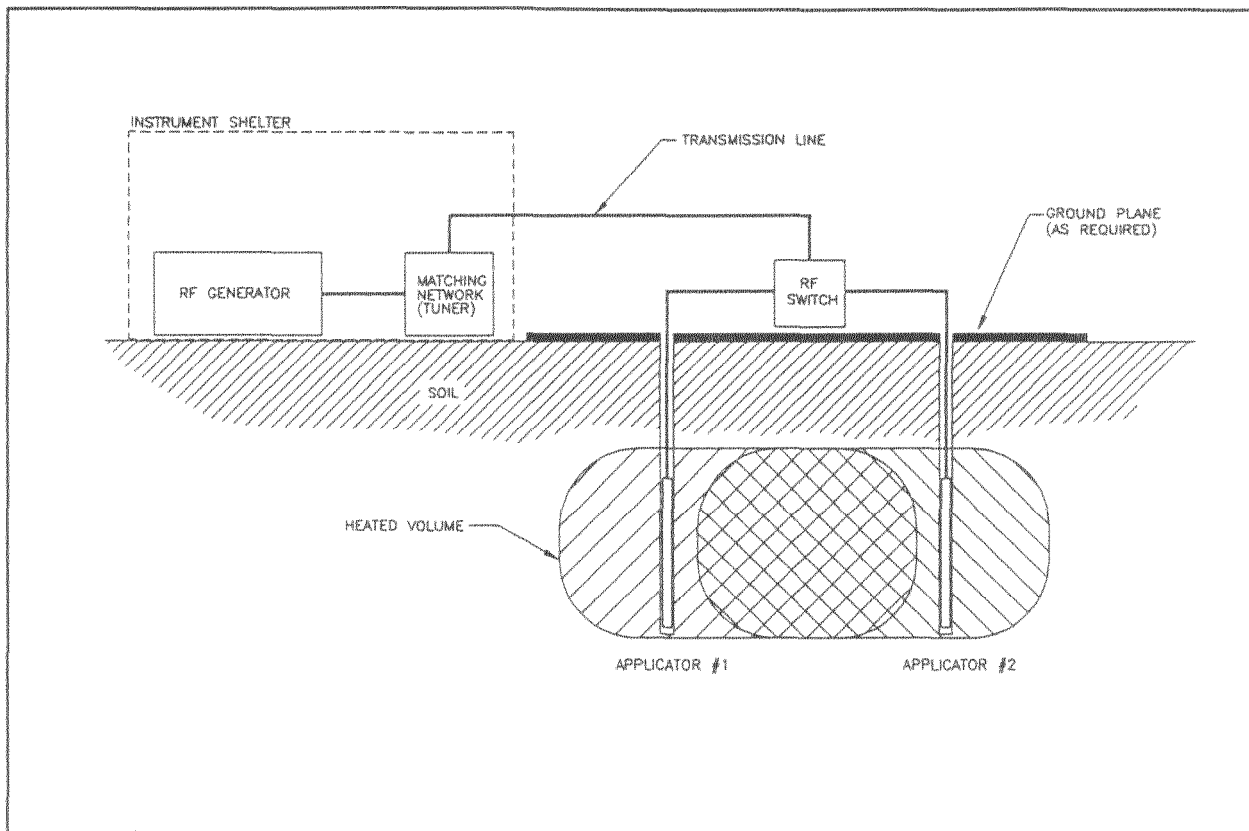


1 Mobile RF heating system with removable instrument shelter, storage trailer and a utility tow vehicle.

Figure 3 shows the switched, dual applicator configuration that was used for the Kelly program. The RF generator is connected alternately to applicator #1 and applicator #2 under computer control.



2 Block diagram of an RF heating system.



3 Block diagram of a switched, two applicator system as implemented for the Kelly program.

Figure 4 is a top view of the Kelly site configured with the shelter, RF switch #3 and the RFH applicators (antennas) in place under two emplacement towers.

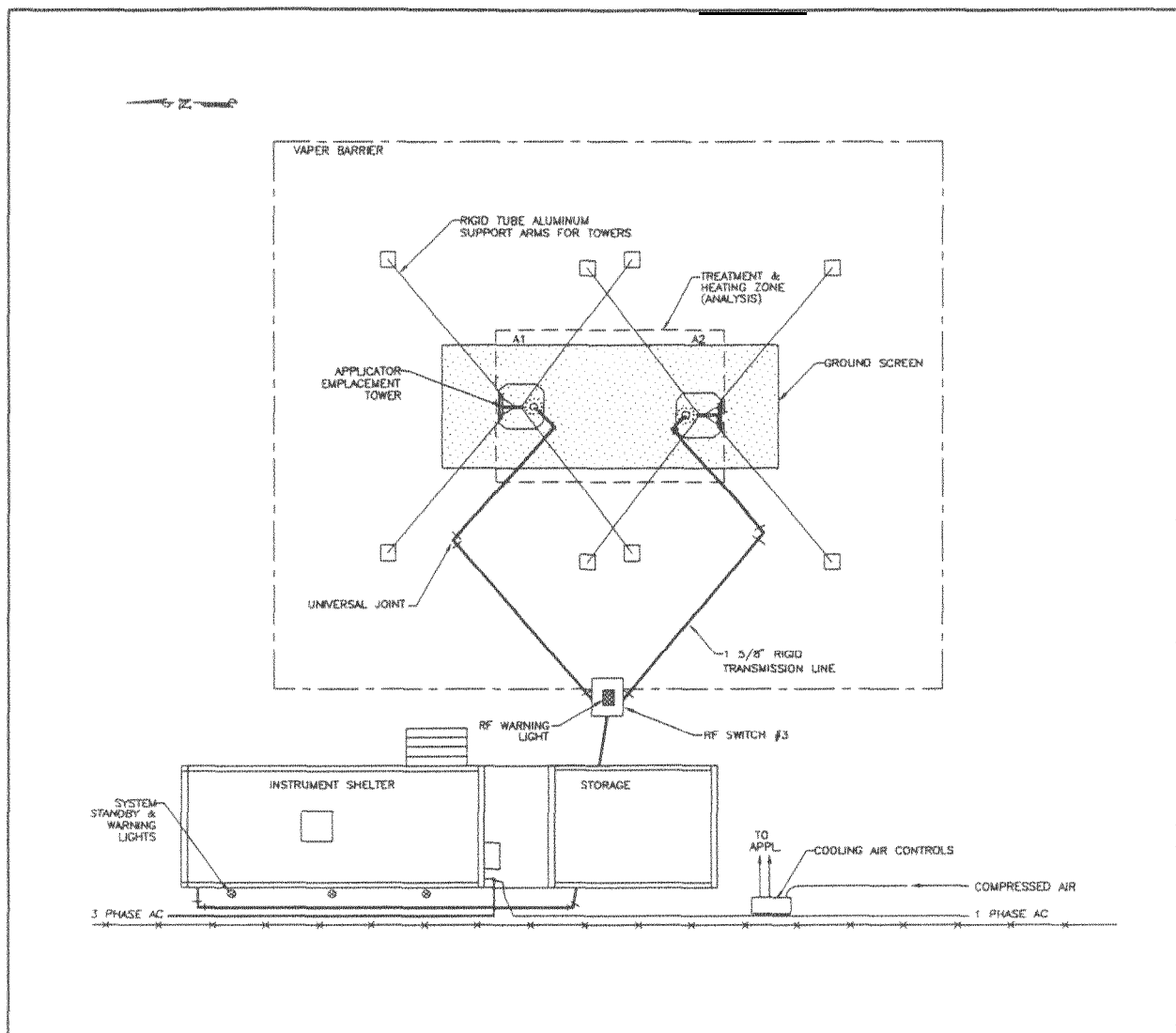
2.1 Detailed RFH System Specifications

This section is adapted from a more detailed text provided in section 2.0 of the KAI appendix supplied to the Brown and Root Report. This summary provides technical details on a number of system components that are listed in Figures 1, 2, 3 and 4.

The equipment groupings described here are appropriate for a full-scale pilot testing system or the master control unit of a two or four generator phased array RFH system. The diagnostic and environmental monitoring equipment can be shared among a number of system modules and does not have to be duplicated for each additional RF generator added to the site.

2.1.1 Basic Mobile RFH System

This system was designed, developed and integrated by KAI Technologies Inc. of Woburn, MA and its Western Field Office in Provo, UT. The principal components, as shown in Figures 1, 2, 3 and 4 are:



4 Plan view of the RF heating system trailer and heating applicators as configured for the Kelly program tests.

Instrument Shelter: 8 ft. x 8 ft. x 20 ft. insulated steel utility shelter with HVAC and AC power distribution. The unit features an air-shock isolation rack configured to protect the 25 kW RF generator cabinet and an instrumentation and control rack. The shelter also has a filtered air system to cool the RF generator.

Trailer: A 28-ft flat bed trailer with neck mounted deck and steel shelter is used to transport the shelter. The trailer includes a heat exchanger tank and cooling fluid circulation system for a 25 kW dummy load which is used to setup and test the RF generator. The under deck area also contains four 28-foot applicator storage bays. A typically loaded trailer weighs 20,000 lbs.

Truck: A heavy-duty pickup truck modified for operation with the trailer as a 30,000 lb. GCVW combination highway vehicle mobilizes the system. The truck frame also carries a roof rack system suitable for transport of applicator assemblies of up to 30 feet in length and emplacement tower sections. The truck is used for general site support tasks during a heating program.

2.1.2 Key System Components Within the Instrument Shelter

These components are listed by generic names in the block diagrams of Figures 1 and 2.

AC Power panel: The shelter is equipped to accept 3-phase 208 to 240 VAC power from a utility or Diesel generator source. The shelter has a 3-phase 200 Ampere power panel (WYE and DELTA feed options). The lines are metered with two levels of transient and surge/over-voltage protection. The system also has a 1-phase 100 Ampere, 110/220 VAC panel that is powered from a 3-phase WYE service or a separate 1-phase feed. The 1-phase power distribution system includes a 1 KVA uninterruptable power supply (UPS) to protect critical control and data acquisition functions. The 1-phase panel also controls power for the auxiliary cooling blower of the RF generator as well as for the air conditioning and lighting of the shelter.

RF Generator: RF Power Products model 25,001D generator (built to KAI specifications and with KAI operation and control modifications). Designed for operational compliance under Part 18 of FCC regulations for Industrial, Scientific and Medical (ISM) equipment.

Frequency: 27.12 or 13.56 MHZ operation (crystal controlled)
Emission: A0 (CW unmodulated)
output: 25,000 Watts, tuned output stage (harmonics suppressed)

The output is continuously adjustable from 100 to 25,000 Watts, the maximum power is set by the line voltage of the site's 3-phase power service.

Details: The generator was operated at 27.12 MHZ for this program. The unit is an optimized industrial design with a 3CX15000A7 ceramic vacuum tube output stage and automatic power controls. The modifications include interfaces for remote control and function monitoring.

Matching Network: KAI custom design with proprietary features.
(Tuner)

Frequency: design centers of 13.56 MHZ and 27.12 MHZ for specified impedance transformations.
Power: > 25,000 Watts

Details:	“T” network design with input and output ports using fully shielded 1-5/8” EIA connections to rigid line coax. The unit contains motorized input, shunt and output controls and interfaces to a KAI control and tuning software package.
Controller:	This is function is developed by the integration of a number of commercial components.
Computer:	Industrial Computer Source rack mounted system with 80386 and 80387 processors, 8 MB RAM, 240 MB hard disk with GPIB and modem interfaces.
Software:	The data acquisition software is a customized and proprietary package of capabilities developed for real time control and specialized diagnostic measurements.
Switching:	HP 3488A switch controller with five interface modules to provide contact closures, coaxial switching and TTL sensing/logic interfaces. The unit is interfaced to the RF generator, tuner and RF switches as well as system annunciators and safety monitors.
comm.	Communications with the system is via a high speed error correcting FAX/modem suitable for wireline or cellular communications. The unit is capable of sending a data message to a host computer, a digital display radio pager or a FAX machine. The system also communicates via a UHF radio data voice message link to signal the operators hand held radio or scanner of a system status message.
Diagnostics:	This function provided by a number of commercial components. The items listed here acquire data that is logged by the control computer in a data acquisition mode. Software setup files define if a channel is to be used for control processing for limit alarms, warning or control actions.
Sensing:	Two HP 3457A scanning digital multimeters (DMM) with 22 input channels are used to monitor system voltages, temperatures, pressures, and power levels
Temperature:	Luxtron 790 floroptic thermometer using four fiber optically coupled sensor probes to monitor the Heating Zone.
AC Power:	Ohio Semitronics PC5 and MVT 3-phase Wattmeter and Voltage transducers interfaced to the HP3457A DMM.
Vector Voltmeter:	HP 8508A with frequency coverage from 0.1 to 2000 MHZ with a phase locked sensing channel sensitivity of down to 10 uV (-87

Signal Generator:	HP 8656B with coverage from 0.1 to 990 MHZ and output levels of up to + 13 dBm.
Network Analyzer:	HP 3577B network analyzer with 0.1 to 200 MHZ coverage with an HP 35677A S-parameter test set.
TDR:	Tektronix 1503C time domain reflectometer
Megger:	Biddle model 218650CL with 500 to 5,000 VDC test voltages.
Environmental monitors:	These items are used to measure site conditions, above and below ground. The isotropic probe is used to monitor site safety conditions for USAF ad OSHA compliance. The spectrum analyzer is used to measure RF harmonic emissions for FCC compliance.
Spectrum Analyzer:	HP 8591E analyzer with EMC personality modules.
Biconical antenna:	EMCO 3104A calibrated antenna and insulated tripod. 20 to 200 MHZ calibration.
Isotropic probe:	Holiday model HI-3012 with MSE and HCH probes. A foam spacer ball for 0.1 m near contact measurements (FCC defined specification).
Thermocouple readout/calibrator:	Omega CL 23 type T digital readout used for all on site temperature measurements of thermocouples.
Weather:	Davis Instrument Weather station II with dewpoint and rainfall sensors.
IR Probe:	Omega model OS36-T-240 passive IR thermocouple unit with type T output mounted on a PVC extension probe.

2.1.3 Key System Components Outside of the Shelter

These components are listed in the diagrams of Section 2.1. The use of these components will vary greatly with the site configuration.

Transmission lines: 1-5/8" rigid copper coaxial lines were used throughout system for system interconnections and to transfer power to the heating antennas. The transmission lines were pressurized with 5 to 15 PSI nitrogen and delivered power to either, heating antenna through a computer controlled, motorized RF switch. Delivery of power to the antenna is typically > 98% efficient for these transmission components.

RF Switch #3: Dielectric model A 50000-203, pressurized, heated, 1-5/8" EIA flange connections. The switch is housed in a weatherproof, secure housing with adjustable legs and universal joints on each of the ports connections.

Applicators: Two KAI 3.5" antenna assemblies designed for subsurface RFH applications (KAI-0690-30).

Frequency: design centers of 13.56, 27.12 or 40.68 MHZ can be configured.
Power: 25,000 Watts
Diameter: 3.5" OD w/o centralizing spacers
Length 7.38' to 11.38' span set for soil conditions (27.12 MHZ)
VSWR: Set by adjustments of length, typically < 1.5, working max is set by the power level, frequency and nitrogen pressurization level.
Feedline: 1-5/8" EIA flange
Details: The antennas are adjustable length, dipole-type, end-feed structures with 1-5/8 in. EIA feedlines. The standard design employs aluminum radiating elements with Teflon insulating components. The use of Teflon limits its to operation to an ambient temperature of 200 degrees C (392 deg. F). Operation can be extended above this temperature by the use of ceramic insulating components and/or localized cooling of the applicator assembly by compressed air.

Guide tubes:
(Sleeves) The applicators were vertically emplaced in a vertical boreholes lined with 4.5 inch ID high temperature fiberglass liners. The liner wall thickness was nominally 0.25 in. and the outside diameter was 5 inches.

Ground planes: The antenna counterpoise/ground plane at the soil surface consists a 8 ft. x 22 ft. x 0.062 in. expanded aluminum mat pattern mat, extended around and between the 3 ft. x 3 ft. x 0.25 ft. thick aluminum ground plane base plates are located around each borehole sleeve liner. An 18 ft. diameter pattern of twelve aluminum radials of #2 insulated aluminum cable extend from each base plate. The perimeter cables are terminated to form an 18-foot diameter aluminum radial pattern of #2 Aluminum cable terminated by 5/8 inch OD x 4 foot copper-clad steel ground rods driven about 45 inches into the soil. The radials are centrally capped by an aluminum screen mat that is bonded to the radials. The antenna transmission lines and supporting structures are bonded to the ground plane at multiple points. NOTE: ***This structure can be simplified for many installations and could have been in this case since the electromagnetic emission levels were well below all safety and harmonic emission requirements.***

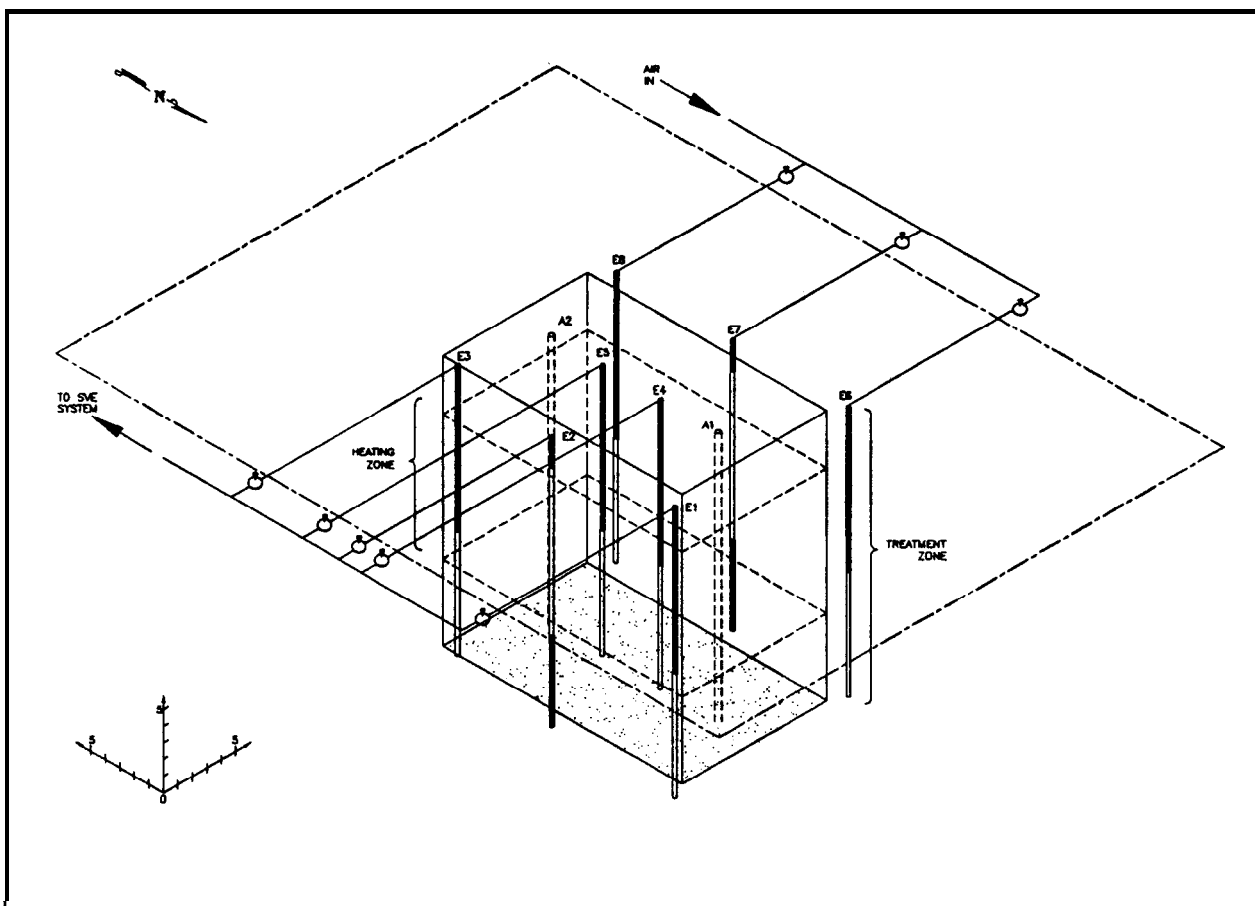
Towers: The emplacement towers are mounted to the 3 ft. x 3 ft. aluminum base plates. The towers are constructed from 10-foot lengths of aluminum antenna mast sections. The masts are jointed to form 10 ft., 20 ft. or 30 ft. emplacement towers. The towers are supported with four aluminum extension tubes with anchored base pads suitable to make the towers self supporting without the use of guy lines. The complete tower includes a 1,500 lb. winch and two rope pulley lines.

3.0 REVIEW OF SOIL CHEMICAL ANALYSIS

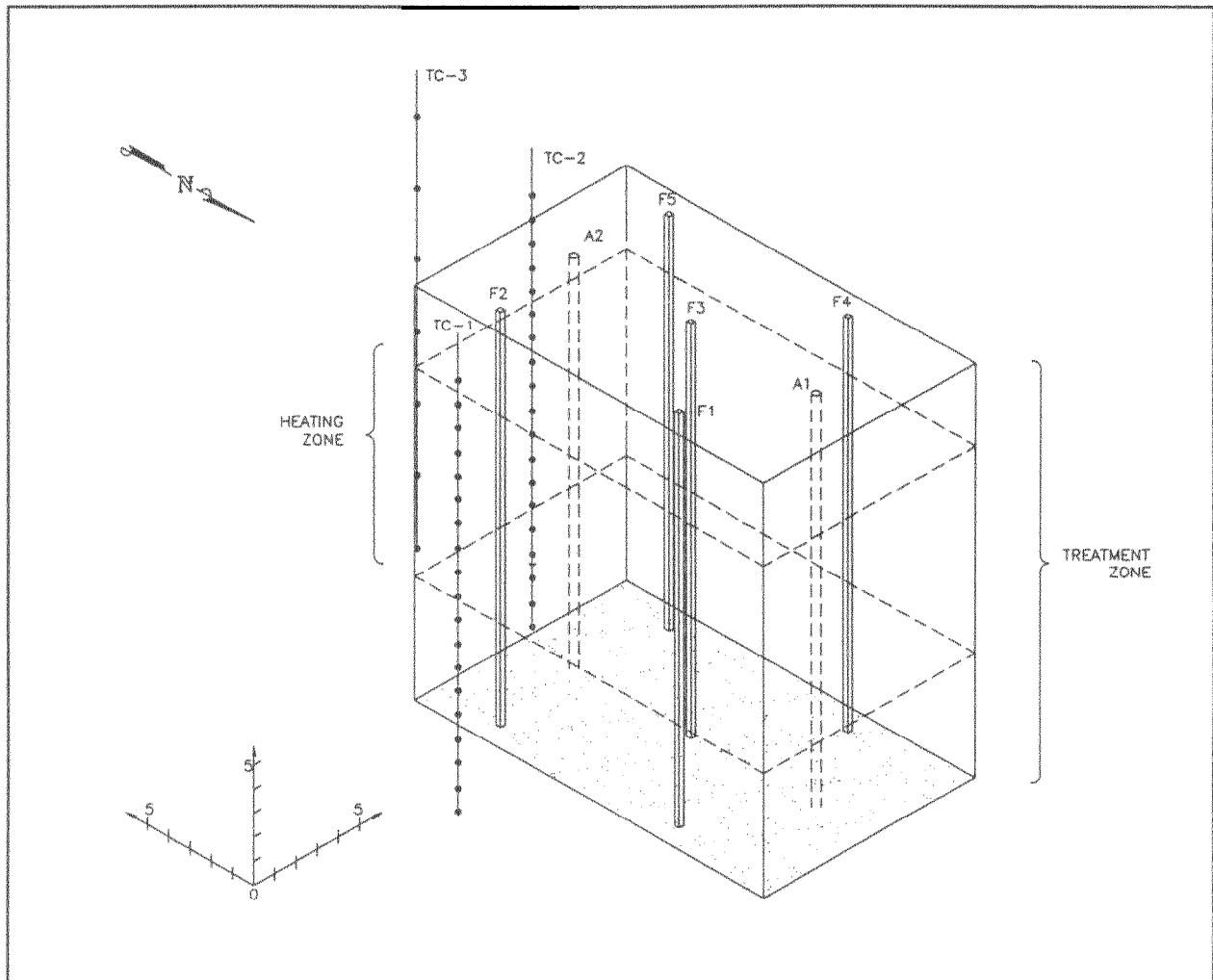
Adapted from section 7.0 of the KAI appendix to the Brown and Root report.

The soil chemical analysis scheme was originally based on the definition of a treatment zone volume of 111 cubic yards (15 ft. x 10 ft. x 20 ft.) which was compared to a control sample region bounding the sides of the volume with sample depths of up to 10 feet below the region. The soil analysis for Total Recoverable Petroleum Hydrocarbons (TRPH) was based on the analysis of 40 sample pairs within this region.

Due to changes in the heating system configuration, a heating zone of 15 ft. x 10 ft. x 10 ft. was defined inside of the treatment zone. The top of the zone starts at a depth of 4 feet and ends at a depth of 14 feet. This zone was further subdivided for analysis into two halves. The halves are centered about each of the heating wells (A1 and A2). Figure 5 is an isometric view of the zones with the heating applicator wells (A1 and A2) and the screened SVE wells (E1 to E8). Note that the open, non-black, regions of the SVE well representations are screened sections of pipe that allow air input or extraction from the treatment zone. Figure 6 is a similar view with the monitoring wells (F1 to F5) shown in addition to the heating wells and three of the temperature monitoring thermocouple strings (TC-1 to TC-3).



5 Isometric view of applicator and SVE wells with piping.



6 Isometric view of applicator and monitoring wells.

The TRPH analysis of these zones, with a >80% confidence level correlates with the energy applied to the zone and the period of the applied energy (heating).

	Volume (cu. yds)	TRPH (%)	Energy Delivered (KWH)	Days Spanned
Treatment Zone	111	29	15,549	49.92
Heating Zone	55.5	49	15,549	49.92
Heating Zone by Applicator, A1 + A2 = Heating Zone Volume				
A1 Heating Zone	27.7	NA	4,348	8.15
A2 Heating Zone	27.7	44	11,201	41.77*

* 2 spans, 28.9 and 12.87, with a cooling period between cycles.

The A2 heating zone, driven by applicator #1, is suggestive of an anticipated recovery rate for the energy applied. Ideally this zone and the A1 zone would have each received 10,000 KWH in a 42 day period. It is projected that this type of heating program would have been more effective than the slow heating period with cooling cycles that this sequence experienced. It is also expected that if a second generator were used, the simultaneous, phased-array heating would have produced an even stronger and more rapid heating effect that would have further improved recovery. Finally, changes to the SVE system design would also be a source of significant recovery improvement.

3.1 Impact of Changes in the Heating System Configuration

Changes in the heating program's planned operating time and its ISM operating frequency required that the heating zone be defined as approximately the upper half of the treatment zone. This change occurred when an ISM operating frequency of 27.12 MHZ was chosen in contrast to a 13.56 MHZ frequency. The 27.12 MHZ frequency was chosen to allow a faster heating of two smaller adjacent volumes within the treatment zone as opposed to a larger heating zone with a slower heating rate.

The 13.56 MHZ applicator would have had a nominal heating span of 18 feet. as opposed to the 9 foot. span of the 27.12 MHZ applicators and could have been positioned within the center of the treatment zone. Two, more rapidly heating, 27.12 MHZ applicators were chosen to be driven in a time-multiplexed heating mode by a single 25 kW RF generator to approximate the performance of a more optimally configured dual RF generator system. This configuration allowed data to be gathered that would be predictive of how a dual RF generator **phased-array**⁸ RF system might perform.

A additional impact of the thinner, vertical profile, heating span occurred when the applicator was fixed in the upper half of the treatment volume. This upper half favored the heating of VOCs as opposed to SVOCs in the lower half of the treatment zone.

3.2 Other Operating Details With Soil Analysis Influence

The SVE system typically operated in a "deep extraction" mode that pulled vapors down from the bottom of the heating zone into the extraction wells screened from 10 ft to 20-ft. depths (see Figure 5). The effect of this downward vapor "draw" may be responsible for some contaminant migration from the heating zone into the treatment zone and is likely to make it difficult to quantitatively evaluate contaminate concentration changes.

Several of the statistically defined TRPH sample sets were complete enough at test well locations to be examined as a concentration profile. A review of some TRPH sample sets suggest that contaminants condensed between the 0-foot and 4-foot levels where the SVE efficiency was low. Condensation also appears to have occurred where soil heated and cooler ambient soil air mixed near the screened entrance to an extraction well. The following data listings are of three sets of soil samples. Missing depths were due to the statistical sampling scheme used to distribute the 40 sample pairs, no data exists at these points.

⁸ A 2-element phased applicator array actually has a heating rate and intensity advantage over what can be produced by two, non-phase-controlled applicators and RF generators. This testing approach provided data to evaluate how well the base heating rate could be predicted for the non-phased applicators. The test also demonstrated the electromagnetic field coupling levels that could be achieved between the two applicators.

A2 - Location- of applicator #1 with the majority of applied energy – The 0 to 4 foot locations show significant increases in concentration. The heating zone volume near the applicator shows a strong removal trend. The 10 to 12 foot location that corresponds to the highest heating temperature profile shows significant removal.

Location A2	Pretreatment Concentration (ppm)	Post treatment Concentration (ppm)
0-2ft.	2,330	8,850 [suggested condensation]
2-4ft.	203	2,570 [suggested condensation]
—— heating zone boundary ——		
4- 6ft.	1,530	154
6- 8ft.	-	-
8 - 10 ft.	-	-
10 - 12 ft.	1,290	33.3 [removal to quantitation limit]
12 - 14 ft. 622	106	
—— heating zone boundary ——		
14 - 16 ft.	-	-
16 - 18 ft.	79,700	20,800
18-20ft	39,300	28,300 [removal by ambient air SVE only]

E5 - Extraction well located on center line near A2 – Extraction is enhanced in the heating zone. The 12 to 14 foot level appears to a condensation boundary were cool air meets the downward flow of hot vapor.

Location E5	Pretreatment Concentration (ppm)	Post treatment Concentration (ppm)
0-2 ft.	-	-
2-4ft.	-	-
—— heating zone boundary ——		
4-6ft.	2,710	673
6-8ft.	1,530	587
8 - 10 ft.	-	-
10 - 12 ft.	668	330
12 - 14 ft.	739	1,450 [suggested condensation at extraction well]
—— heating zone boundary ——		
14 - 16 ft.	-	-
16 - 18 ft.	-	-
18-20ft	105,000	35,800 [removal by ambient air SVE]

F3 • Monitor hole for IR temperature profiles centered between A1 and A2 at 5 feet — Strong removal is suggested in the top of the heating zone where the maximum temperature profiles were recorded between 6 and 10 foot. The temperature dropped off sharply in the 10 to 12 foot zone and could be seen to match the region of increased concentration.

Location F3	Pretreatment Concentration (ppm)	Post treatment Concentration (ppm)
0 - 2 ft.	-	-
2 - 4 ft.	-	-
—— heating zone boundary ——		
4 - 6 ft.	4,920	702 [strong removal suggested]
6 - 8 ft.	-	-
8 - 10 ft.	-	-
10 - 12 ft.	336	4,510 [suggested condensation between extraction wells screened from 10 ft. to 20 ft.]
12 - 14 ft.	-	-
—— heating zone boundary ——		
14 - 16 ft.	-	-
16 - 18 ft.	-	-
18 - 20 ft.	-	-

4.0 REVIEW OF SOIL VAPOR EXTRACTION DATA

Adapted from section 8.0 of the KAI appendix to the Brown and Root report.

The soil vapor extraction system flow characteristics do not appear to have been optimum to extract from the chosen heating zone in the upper level of the site treatment zone (see screened well configuration shown in Figure 5 of Section 3.0 of this document). However, it appears that they were adequate to demonstrate significant VOC removal from the heated zone.

The downward “draw” of the SVE system on the heated zone has been observed to produce a number of thermal profile measurement distortions that require careful analysis for interpretation. In general, the downward flow caused the deep portions of the thermal patterns to have lower relative temperature values and truncated profile patterns with minimal lateral flow and limited “draw” from the higher levels of the zone. It is also very possible that condensation occurred for some volatiles as they mixed with cooler air as they were drawn to the extraction wells.

The SVE system output temperatures, measured at the control valves next to the vacuum manifold, were generally lower than anticipated. Temperatures within the heated zone suggested that the high temperature soil vapors could be estimated to range from 100 degrees C to well over 180

degrees C (+230 degrees is likely). These vapors were mixed with a significant **volume**⁹ of cool subsurface air that maintained the extraction well output temperatures well below 100 degrees C (as measured by average reading temperature probes).

Figure 7 is a simplified representation of the conditions within the RFH zone. The sensor well is a monitoring well such as FI which was located three feet from a heating applicator well. The RF energy incident on the soil from the heating antenna directly **interacts**¹⁰ with water droplets, hydrocarbon deposits and sand represented in this figure. The RF interaction causes each of these items to heat as an **isolated point source**. **The** heating rates differ for each of the items. At a given point in the heating program the hydrocarbon deposit points may be heated to a temperature of perhaps 200 degrees C while the water droplets are just approaching 90 degrees C. The sand at this point may only be heated 5 degrees above an ambient temperature of 23 degrees C to perhaps 28 degrees C (unless the sand particle has a hydrocarbon or water droplet on its surface and it then is heated by conduction to a higher average temperature).

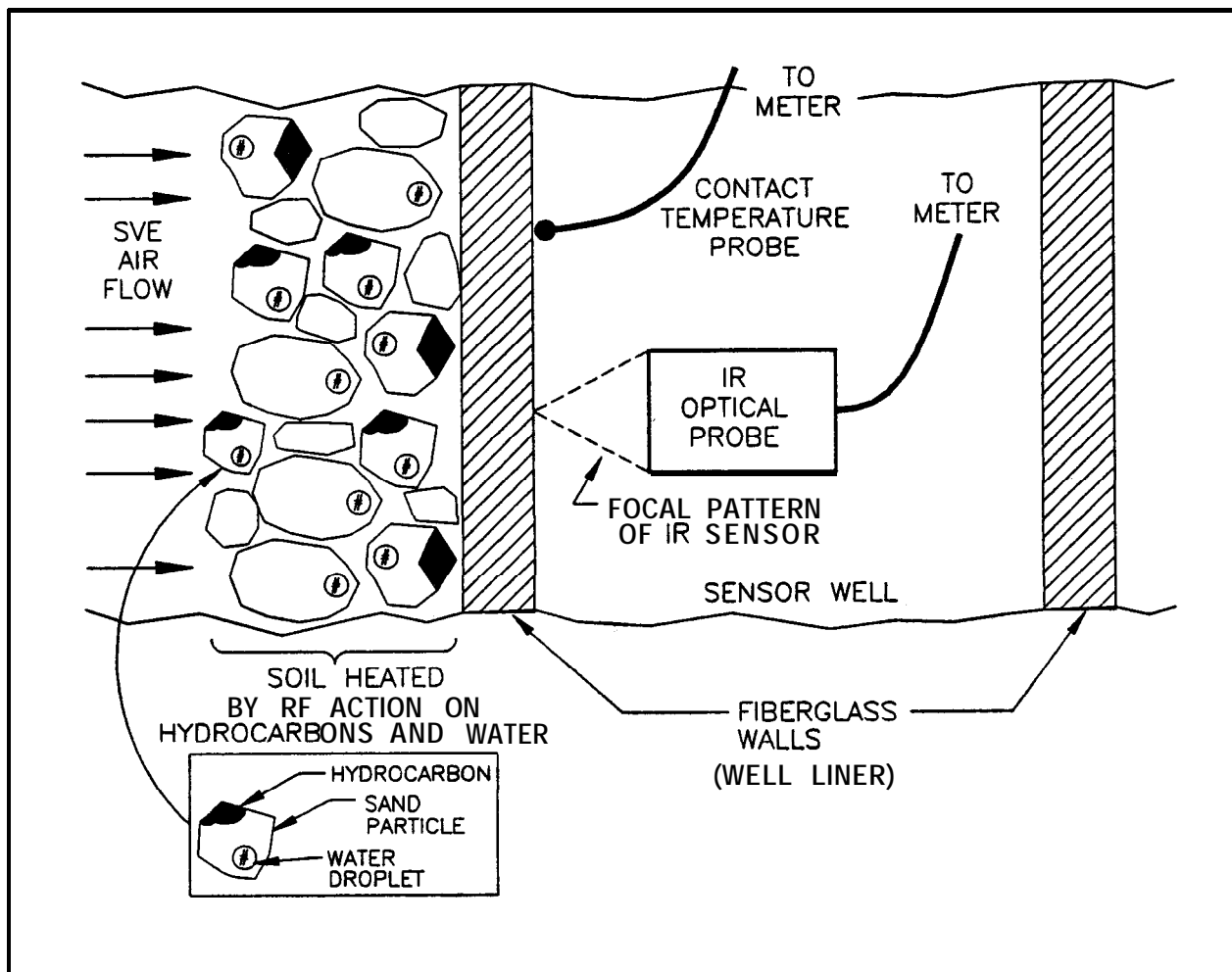
The underground SVE air flow pattern draws ambient, 23 degree C, soil air into the heating zone. The RF illuminated soil heats the 23 degree ambient air passing through the soil matrix to a higher temperature. **However, this temperature is still well below the highest point source temperature of 200 degrees C for this example.**

In Figure 7 the soil-heated air flows past the fiberglass wall of the sensor well. The air heats the wall to a temperature that approximates that of the air **but is typically much lower in temperature than the point sources that heated the air**. **The** probes within the sensor well measure the wall temperature. The infrared (IR) probe is the most accurate measurement since it optically focuses on a small spot and does not average its thermal mass with that of the contact point on the wall. This kind of probe is best for rapid temperature profiling but does not provide an absolute measurement of the average wall temperature. Movement of the probe mixes air within the well and further diminishes the absolute accuracy of the measurement. The contact probe can provide more accurate measurement of the wall temperature if the volume behind the probe is filled with a barrier that stops air from flowing near the probe. The probe needs to be in contact with the wall in excess of 5 minutes to obtain an accurate reading.

It is important to note that for the Kelly program, all of the sensor wells were also surrounded with 0.5 to 2 inches of dry sand. This sand layer further separated the fiberglass wall from the heated soil matrix and enhanced the air flow in this region. **It is on this basis that all ZR temperature measurements were considered low by a conservative 10 to 20 degrees and in reality may have been 40 to 100 degrees below the actual point source heating temperatures.**

⁹ This conclusion is arrived at by estimating that the top 1/3 of each extraction well (10 ft. to 13 ft.) received hot vapors and the balance of the well (13 ft. to 20 ft.) contributed cooler subsurface air to the extracted air stream. In cases where multiple extraction wells were connected, the dilution ratio was still higher.

¹⁰ Radio frequency (RF) energy desorbs and mobilizes the contaminants more effectively than heat conduction by steam or hot air because thermal activation of the contaminant occurs at the molecular level throughout the RF treatment volume. The dipole-dipole bonding between contaminant molecule and soil particle is thermally agitated at the bonding site by the RF energy.



7 Simplified diagram of indirect temperature measurements of soil temperature in the heating zone under SVE influence.

The peak measured temperature¹¹ of 233.9 degrees C by a point sensor on the outside of a fiberglass well liner suggested that a hot liquid flowed into the vicinity of the sensor and blocked all air flow into the region of the sensor. The **liquid was heated to a temperature of perhaps 240 degrees or more within the heating zone near the sensor well. This is likely to be the temperature of many of the isolated hydrocarbon contaminant heating sites distributed throughout the heating zone.**

There are three important trends to consider in interpreting temperature data for this program.

- Increasing permeability increases air flow and lowers measured temperatures - When contaminants and water are removed from the region surrounding the heating applicator wells, the permeability of the soil increases. Increased permeability increases the SVE air flow volume within the heated region. This trend lowers the measured temperature in the monitoring wells due to increased flow and air mixing.

¹¹ This peak was part of a slow trend that stayed above 200 degrees for several hours for this well and corresponded in a high reading at an adjacent well sensor at the same depth.

- **Contaminant removal lowers the heating rate near sensor well regions** - As water and RF heated contaminants are removed from the heating zone near the applicator wells and the sensor wells, the heat generation rate drops to a lower “sand-like” heating rate. The regions with removed contaminants become somewhat “cooler” than the regions on the outer boundaries of the heating pattern that continue to have strongly heating contaminants.
- The expansion of the heating pattern beyond the sensor wells will lower the measured temperatures at the interior well locations - The increased permeability, contaminant/water removal, increased available soil air mixing volume and the increasing distance of the heating front from the sensor wells may all contribute to the measurement of lower relative temperatures as the heating program progresses.

5.0 COST PROJECTIONS FOR AN RFH SYSTEM

Adapted from section 9.0 of the KAI appendix to the Brown and Root report.

The Kelly RFH program was essentially executed as an investigative pilot program that addressed a number of site configuration items (e.g. SVE) in addition to the RFH system installation and operation. The site was operated with more personnel than would normally be required for even a larger heating site. The program and site conditions did not allow for the progressive expansion of the heating zone or full automatic operation of the heating system. These two factors make it difficult to directly scale the costs of the Kelly program to a commercial embodiment of an RFH system.

However, there are some cost and resource utilization numbers available, directly from the program data, that can be used to generally characterize the application of RFH for thermally enhanced SVE programs. These numbers were based on the last 21.3 day **period**¹² of the heating program. These planning numbers are:

- RF Energy Generation rate: 19.93 kW/hour
This rate is dependent on the available 3-phase AC utility voltage level. AC line voltage set a 22 kW peak power operating level for this site.
- Cost per hour of RF generated: \$3.88/hour
This cost is based on a 19.93 kW/hr generation rate with a 58.9% system 3-phase AC power conversion efficiency plus 5 kWh overhead with a utility rate of \$0.10/kWh.
- RF system operation within on-site span: 94.54%
This operation period includes breaks for measurements and maintenance checks over a span of 10 days or more.

¹² This period follows the repairs to the 3-phase power system splices and replacement of the power line.

5.1 Outline for Costing of a 200-kW System

A 200-kW system could be developed by using eight 25-kW RF generators with the capability of driving either 2-element or 4-element applicator arrays. The system would employ a minimum of 16 switched applicator positions to allow continuous operation of the system as applicators are removed from heated areas and installed in new areas. The exact definition of a 200-kW system will depend on the site characteristics. Some of the principal determinates of the system configuration would be:

- Contaminant plume thickness, extent and nominal depth defines if the preferred access is through either vertical or horizontal drilling techniques.
- The preferred heating dimensions of the plume will determine if the RFH system's operating frequency should be 13.56 MHZ with a nominal heating span of 18 ft. or 27.12 MHZ with a nominal span of 9 feet. It is also possible to operate with a 6 foot span if a 40.68 MHZ frequency is used. In some cases the heating rate of the plume will be a factor in contrast to SVE flow requirements. An ISM heating frequency of 40.68 MHZ heats the smallest volume most rapidly and 13.56 MHZ heats the largest volume more slowly.
- The need or option to access large volumes of the contaminant plume also determines if the system needs large numbers of installed applicators with switching networks to allow efficient, automated operation. Alternately a limited number of applicators, with computer controlled mechanical positioning equipment, can incrementally heat large volumes of the plume from a few boreholes (e.g., horizontal).

5.2 A 200-kW System Description

The following system would be defined as a wide coverage 13.56 MHZ system configured for horizontal drilling emplacement. It would have the following components:

- 2 RF Master control and instrument trailers with an internally mounted 25 KW, 13.56 MHZ RF generator and tuner (the units would be similar in size and design to the KAI pilot Rig #1 used for this program). Each master control trailer would also carry control and diagnostic instrumentation. The master control systems would be linked with the slave systems through fiber optic cables. Each master control system would be fully automated and respond to both local and remote control computer commands.
- 2 Slave RF systems with three 25 kW, 13.56 MHZ RF generators and tuners per trailer. Each slave trailer would include a common cooling system and 3-phase AC power distribution system. Flexible and rigid RF transmission lines suitable for the operating frequency would be used to reach the 16 heating locations from the two trailer groups of master and slave units.
- 16 Flexible horizontal applicators with an emplacement system allowing controlled motion during heating of up to 45 ft. per setup.
- 8 Motorized RF switches to select between two installed applicators that are to be selected by each RF generator/tuner group.

- 1 3-phase AC power utility or Diesel generator service capable of providing a minimum of 500 kVA for the site. Additional power requirements would depend on the requirements of the SVE and off gas treatment systems.

A heating system of this scale and capital **investment**¹³ can be expected to operate in the field with utility power costs, full automation, and programmed personnel support for configuration changes at a cost of much less than \$100 per cubic yard over a multi-year operating period. This figure is exclusive of horizontal drilling costs, SVE system installation, off gas treatment and non-RF site operating costs.

5.3 Recommendations on System Strategies

The costing of RF thermally enhanced SVE programs is very dependent on the use of the following key strategies:

- Select the ISM heating frequency based on the optimum heating rate, soil penetration depth, and contaminant thickness.
- Select a drilling technique (vertical, slant or horizontal) that provides the most access to the contaminated zone for each borehole position and applicator heating span.
- Use each heating applicator in multiple positions along the length of the guide tube or slowly “scan” the heating zone with the applicator’s heating span.
- Use each RF generator to sequentially drive two or more applicators.
- Use multiple RF generators in groups of two or four as phased arrays to focus and steer the heating pattern.
- Use automated and remote control operation to minimize the need for highly skilled on-site labor.

The application of RF thermal enhancement also needs to be characterized in terms of the time savings it represents over conventional treatment projections using non-thermal SVE technique at the same site (assuming the targeted contaminants are removable on a realistic time scale by non-thermal methods). Key points for consideration are:

- RF thermal enhancement can be applied as a rapid response tool for stopping the migration of contaminant plumes at depths of over 750 feet.
- RF thermal enhancement may be selectively applied to high concentration, “hot spot” regions within a general site remediation strategy using passive SVE, bio-venting or bio-remediation.
- Thermally enhanced SVE may allow extraction of contaminants from some sites that normally would require excavation.

¹³ Assuming a 5 year pay pack period.